



RESEARCH CENTER
Sophia Antipolis - Méditerranée

FIELD

Activity Report 2013

Section New Results

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AXIS Project-Team

6. New Results

6.1. Introduction

Our new results are split into our three sub-objectives as described in Section 3.1 :

- **Sub-Objective 1: Mining for Knowledge Discovery in Information Systems:**

This year we obtained ten main results (cf. Section 6.2): five on Clustering methods, four on how to apply these clustering methods on real data and finally one related to the use of ontology for Multi-View KDD process.

Let us note that two 2011 results have been published this year as book chapters [34], [31].

Chongsheng Zhang published also his work conducted during his Explore programm at UCLA (USA) when, as AxIS PhD student, he was visiting the WIS team of Prof. Carlo Zaniolo at UCLA in 2010 [26].

- **Sub-Objective 2: Information and Social Networks Mining for Supporting Information Retrieval:**

This year, we pursued our two main works on this topic (cf. Section 6.3):

- the detection of communities in a social network (detection of graphs extracted from relational data) (cf. Section 6.3.1),
- the multi view clustering of relational data (cf. Section 6.3.2).

- **Sub-Objective 3: Interdisciplinary Research For Supporting User Oriented Innovation:**

With the expansion of the innovation community beyond the firm's boundaries (the so-called "open innovation") a lot of changes have been introduced in design and evaluation processes: the users can become co-designers, HCI design and evaluation focus is no longer placed on usability only but also on the whole user experience [70] [11] , experimentations take place out of labs with large numbers of heterogeneous people instead of carefully controlled panels of users etc.

All these deep changes required improvements of existing practices, methods and tools for the design/evaluation of information systems as well as for usage analysis. This evolution called also for a structured user-centred methodology (methods and ICT tools) to deal with open innovation. Various different disciplines and trends are dedicated in understanding user behaviour on Internet and with Digital Technologies, notably Human Computer Interaction community (HCI), Computer Supported Cooperative Work (CSCW), Workplace Studies, Service Design, Distributed Cognition and Data Mining.

Our contribution to open innovation research related to ICT-based services or products keeps its focus on usage analysis and user experience measurement for design, evaluation and maintenance of information systems and our activities from 2011 have been conducted both breadth wise and in depth with two main objectives :

- Improving design and evaluation support tools and methods for user driven driven innovation,
- Development of the FocusLab platform

This year, our research was conducted along three focus:

- Extension of usability methods and models (cf. Section 6.4). First we pursued our work on User Evaluation and Tailoring of Personal Information in the context of the ANR project PIMI. Second a paper related to our strategy and heuristics for rural tourist web sites benchmarking elaborated in the context of the Pacalabs project HOTEL-REF-PACA is written for submission in 2014;
- Designing and evaluating user experience in the context of a living lab: this year five results came from ELLIOT project (cf. Section 6.5) such as an environmental data platform based on citizen sensing, low-cost sensor, user experience measurement, user behaviour change analysis, studies of persuasive technologies and gamification in Energy economy and green services.
- FocusLab Platform (cf. Section 6.6).

6.2. Mining for Knowledge Discovery in Information Systems

6.2.1. Fuzzy Clustering on Multiple Dissimilarity Matrices

Participants: Yves Lechevallier, Francisco de Carvalho.

During 2013 we introduce fuzzy clustering algorithms [18] and [27] that can partition objects taking into account simultaneously their relational descriptions given by multiple dissimilarity matrices. The aim is to obtain a collaborative role of the different dissimilarity matrices to get a final consensus partition. These matrices can be obtained using different sets of variables and dissimilarity functions. These algorithms are designed to furnish a partition and a prototype for each fuzzy cluster as well as to learn a relevance weight for each dissimilarity matrix by optimizing an adequacy criterion that measures the fit between the fuzzy clusters and their representatives. These relevance weights change at each algorithm iteration and can either be the same for all fuzzy clusters or different from one fuzzy cluster to another.

A new algorithm [19] based on a non-linear aggregation criterion, weighted Tchebycheff distances, more appropriate than linear combinations (such as weighted averages) for the construction of compromise solutions is proposed.

Experiments with real-valued data sets from the UCI Machine Learning Repository (<http://archive.ics.uci.edu/ml/>) as well as with interval-valued and histogram-valued data sets show the usefulness of the proposed fuzzy clustering algorithms.

6.2.2. Clustering of Functional Boxplots for Multiple Streaming Time Series

Participant: Yves Lechevallier.

We introduced a micro-clustering strategy for Functional Boxplots [30]. The aim is to summarize a set of streaming time series split in non overlapping windows. It is a two step strategy which performs at first, an on-line summarization by means of functional data structures, named Functional Boxplot micro-clusters; then it reveals the final summarization by processing, off-line, the functional data structures. Our main contribution consists in providing a new definition of micro-cluster based on Functional Boxplots and, in defining a proximity measure which allows us to compare and update them. This allows us to get a finer graphical summarization of the streaming time series by five functional basic statistics of data. The obtained synthesis will be able to keep track of the dynamic evolution of the multiple streams.

This work is done in collaboration with the laboratory of Political Science "Jean Monnet", Second University of Naples, Caserta, Italy.

6.2.3. Web Page Clustering based on a Community Detection Algorithm

Participant: Yves Lechevallier.

Extracting knowledge from Web user's access data in Web Usage Mining (WUM) process is a challenging task that is continuing to gain importance as the size of the Web and its user-base increase. That is why meaningful methods have been proposed in the literature in order to understand the behaviour of the user in the Web and improve the access modes to information.

During 2013 we pursued our previous work on our approach for extracting data based on the modularity function. This approach discovers the existing communities by modeling the data obtained in the pre-processing operation as a weighted graph. The method discriminates the communities through their subject of interest and extract relevant knowledge.

This work is done in collaboration with Yacine Slimani from the LRIA laboratory at the Ferhat Abbas University, Setif, Algeria and will be submitted to an international journal.

6.2.4. Normalizing Constrained Symbolic Data for Clustering

Participants: Marc Csernel, Francisco de Carvalho.

Clustering is one of the most common operation in data analysis while constrained is not so common. During 2013 we presented a clustering method [31] in the framework of Symbolic Data Analysis (S.D.A) which allows us to cluster Symbolic Data. Such data can be constrained relations between the variables, expressed by rules which express the domain knowledge. But such rules can induce a combinatorial increase of the computation time according to the number of rules. The algorithm presented a way to cluster such data in polynomial time. This method is based first on the decomposition of the data according to the rules, then we can apply to the data a clustering algorithm based on dissimilarities.

6.2.5. Dynamic Clustering Method for Mixed Data

Participants: Yves Lechevallier, Marc Csernel, Brigitte Trousse.

For ELLIOT project purposes (cf. Section 7.3.1), a new version of MND method (Dynamic Clustering Method for Mixed Data) has been elaborated. It determines iteratively a series of partitions which improves at each step the underlying clustering criterion. All the proposed distance functions for p variables are determined by sums of dissimilarities corresponding to the univariate component descriptors Y_j . The most appropriate dissimilarities have been suggested above according to the type of variables.

In practice, however, data to be clustered are typically described by different types of variables. An overall dissimilarity measure is obtained by a linear combination of the dissimilarity measures computed with respect to the different kinds of variables.

A new release of MND algorithm based on past work [80] has been developed for ELLIOT purposes, providing some default configuration parameters for non experts.

In this version two types of distances are proposed:

- **Quantitative distance:** the choice is type L1 distance or Euclidean distances when the types of variables are quantitative or continuous.
- **Boolean distance:** the choice is Khi2, type L1 distance or Euclidean distances when the type of variables is categorical or discrete.

This algorithm has been applied to cluster answers at questionnaires issued from a diary tool within the ELLIOT Green Services use case (cf. Section 6.5.4).

6.2.6. Applying a K-means clustering method for districts clustering according to Pollution

Participants: Brigitte Trousse, Yves Lechevallier, Guillaume Pilot, Caroline Tiffon.

Our motivation was to provide citizen a comparative analysis at the district level related to pollution data from Azimut stations (ozone O3 and nitrogen dioxide NO2). To achieve this, the Nice Côte d'Azur territory was discretized into small areas. IoT Data are preprocessed for each district and period of time before applying clustering. The temporal and spatial units were clustered into 5 and then into 6 clusters. The partition into 5 clusters was selected, then the temporal units for each area were counted. For the partition in 5 clusters, for each area the percent of each cluster was counted. Around 30 areas with more than 10 temporal units were found. We improved this to classify different districts of the city based on their IoT data (Azimut data O3-NO2) for each hour/day in order to provide a new functionality in the second version of MyGreenServices.

This work is partially funded by ELLIOT project (see Section 7.3.1).

6.2.7. Summarizing Dust Station IoT Data with REGLO, a FocusLab web service

Participants: Yves Lechevallier, Brigitte Trousse, Guillaume Pilot, Xavier Augros.

Within ELLIOT, we applied the GEAR (or REGLO in French) method [57], [58], [59] on the evolution of dust data issued from one citizen sensor.

Our motivation was to summarize IoT data in order to have a pollution context for each user. Such IoT summaries constitute interesting individual contextual data for supporting the living lab manager to better interpret the user behavior and finally the user experience.

REGLO summarised IoT data with isolated points and line segments.

The goal now is to carry out an analysis of these summaries to automatically determine the characteristics of the curve.

We selected only segments. For each segment we calculated four variables that characterize it:

- The slope of the segment,
- The midpoint of the segment (average of this segment),
- The length of the segment,
- The duration of the segment (the time interval between the start time and the end time of the segment).

From these four values we can achieve an interpretation of the previous curve, taking into account only two variables and constructing a 2D representation.

This work is partially funded by ELLIOT project (see Section 7.3.1).

6.2.8. Clustering of Solar Irradiance

Participants: Thierry Despeyroux, Francisco de Carvalho, Yves Lechevallier, Thien Phuc Hoang Nguyen.

The development of grid-connected photovoltaic power systems leads to new challenges. The short or medium term prediction of the solar irradiance is definitively a solution to reduce the storage capacities and, as a result, authorizes to increase the penetration of the photovoltaic units on the power grid. We present the first results of an interdisciplinary research project which involves researchers in energy, meteorology and data mining, addressing this real-world problem. The objective here is to show interest and disadvantages of two approaches for classifying curves.

In Reunion Island from December 2008 to March 2012, solar radiation measurements has been collected, every minutes, using calibrated instruments. Prior to prediction modelling, two clustering strategies has been applied for analysis the data base of 951 days.

During 2013 we continued our research and obtained many results [28].

Our methodology is based on two clustering approaches. The objective here is to show interest and disadvantages of two approaches for classifying curves.

The first approach combines the following proven data-mining methods. Principal Component Analysis was used as a pre-process for reduction and de-noising and the Ward Hierarchical and K-means methods to find a partition with a good number of classes.

The second approach [78],[20] uses a clustering method that operates on a set of dissimilarity matrices. Each cluster is represented by an element or a subset of the set of objects to be classified. The five meaningfully clusters found by the two clustering approaches are compared.

6.2.9. *Understanding of Cooking User's Recipes by Extracting Intrinsic Knowledge*

Participants: Damien Leprovost, Thierry Despeyroux, Yves Lechevallier.

On community web sites, users share knowledge, being both authors and readers. We present a method to build our own understanding of the semantics of the community, without the use of any external knowledge base. We perform this understanding by knowledge extraction from analysed user contributions. We propose an evaluation of the trust attributable to that deduced understanding to assess the quality of user content, on cooking recipes provided by users on sharing web sites. This work is partially funded by FIORA project (see Section 7.2.2). Two articles have been accepted in early 2014 [25], [29].

6.2.10. *Knowledge Modeling for Multi-View KDD Process*

Participant: Brigitte Trousse.

We pursued our supervision (with our colleagues H. Behja and A. Marzark from Morocco) of E.L. Moukhtar Zemmouri's PhD thesis (Morocco) on a Viewpoint Model in the context of a KDD process, topic we initiated during Behja's PhD thesis [40]). E. Zemmouri defended his thesis at the end of this year [75]. Below is the summary of his PhD thesis.

Knowledge Discovery in Databases (KDD) is a highly complex, iterative and interactive process aimed at the extraction of previously unknown, potentially useful, and ultimately understandable patterns from data. In practice, a KDD process involves several actors (domain experts, data analysts, KDD experts etc.) each with a particular viewpoint. We define a multi-view analysis as a KDD process held by several experts who analyze the same data with different viewpoints. We propose to support users of multi-view analysis through the development of a set of semantic models to manage knowledge involved during such analysis. Our objective is to enhance both the reusability of the process and coordination between users. To do so, we propose first a formalization of Viewpoint in KDD and a Knowledge Model that is a specification of the information and knowledge structures and functions involved during a multi-view analysis. Our formalization, using OWL ontologies, of viewpoint notion is based on CRISP-DM standard through the identification of a set of generic criteria that characterize a viewpoint in KDD. Once instantiated, these criteria define an analyst viewpoint. This viewpoint will guide the execution of the KDD process, and then keep trace of reasoning and major decisions made by the analyst. Then, to formalize interaction and interdependence between various analyses according to different viewpoints, we propose a set of semantic relations between viewpoints based on goal-driven analysis. We have defined equivalence, inclusion, conflict, and requirement relations. These relations allow us to enhance coordination, knowledge sharing and mutual understanding between different actors of a multi-view analysis, and re-usability in terms of viewpoint of successful data mining experiences within an organization. An article selected from the international conference NGNS 2012 [74] will be published in the on-line [Journal of Mobile Multimedia](#), Volume 9 No.3 &4 March 1, 2014.

6.3. Information and Social Networks Mining for Supporting Information Retrieval

6.3.1. *Clustering of Relational Data and Social Networks Data: Graph Aggregation*

Participant: Yves Lechevallier.

The automatic detection of communities in a social network can provide a kind of graph aggregation. The objective of graph aggregations is to produce small and understandable summaries and it can highlight communities in the network, which greatly facilitates the interpretation.

Social networks allow having a global view of the different actors and different interactions between them, thus facilitating the analysis and information retrieval.

In the enterprise context, a considerable amount of information is stored in relational databases. Therefore, relational database can be a rich source to extract social network.

During this year we updated the program developed by Louati Amine in 2011. A book chapter [34] proposes a new aggregation criteria.

This work is done by Louati Amine (AxIS) in collaboration with Marie-Aude Aaufaure, head of the Business Intelligence Team, "Ecole Centrale de Paris", MAS Laboratory.

6.3.2. Multi-View Clustering of Relational Data

Participants: Thierry Despeyroux, Francisco de Carvalho, Yves Lechevallier.

In the work reported in [47] in collaboration with Francisco de A.T. de Carvalho, we introduce an improvement of a clustering algorithm described in [78] that is able to partition objects taking into account simultaneously their relational descriptions given by multiple dissimilarity matrices. In this version of the prototype clusters depend on the variables of the representation space. These matrices could have been generated using different sets of variables and dissimilarity functions. This method, which is based on the dynamic clustering algorithm for relational data, is designed to provided a partition and a vector of prototypes for each cluster as well as to learn a relevance weight for each dissimilarity matrix by optimizing an adequacy criterion that measures the fit between clusters and their representatives. These relevance weights change at each algorithm iteration and are different from one cluster to another. Moreover, various tools for the partition and cluster interpretation furnished by this new algorithm are also presented.

Two experiments demonstrate the usefulness of this clustering method and the merit of the partition and cluster interpretation tools. The first one use a data set from UCI machine learning repository concerning handwritten numbers (digitalized pictures). The second uses a set of reports for which we have an expert classification given a priori. This work has been published this year as a chapter in "Advances in Knowledge Discovery and Management" [32].

6.4. Extension of Usability Methods and Tools

6.4.1. User Evaluation and Tailoring of Personal Information

Participants: Claudia Detraux, Dominique Scapin.

In the context of the ANR project PIMI (Personal Information Management through Internet) an ergonomic evaluation was conducted on the initial prototype, in its PC version [49] and its mobile version [48]. In addition, an experiment was conducted on the usability of the new improved PIMI prototype. The goals were to evaluate its usability, and to assess user tailoring as an evaluation technique. Thirty users participated to the study: a first part consisted in a standard user test (SUT) and a second part was a usability test with tailoring (UTT). Overall, a total of 51 usability problems were diagnosed. Among those, 32 resulted from SUT, and 19 from UTT. Part of the latter (11) are additional to the ones identified during SUT, and to those diagnosed previously by usability inspection (UI with Ergonomic Criteria). The active involvement of users through customization scenarios appear to provide additional cues for usability assessment, and for design, with new generic usability recommendations [23],[22].

6.5. Designing and Evaluating User Experience and Methods for Open Innovation

6.5.1. MyGreenServices: a Pollution Collective-Awareness Platform based on Citizen Sensing

Participants: Brigitte Trousse, Guillaume Pilot, Xavier Augros, Florian Bonacina, Caroline Tiffon, Anne-Laure Negri, Bernard Senach.

Adopting a living lab approach and following an experiential design process [63], we co-created with users and implemented a Pollution Collective-Awareness platform based on Citizen Sensing called "MyGreenServices" [38]. This deployment was very rich in terms of a better understanding of research problems to be addressed in this context in order to lead to user behaviour changes: citizen sensing, environmental crowdsourcing platform and user experience in the context of IoT.

MyGreenServices (<http://mygreenservices.inria.fr>) which was very robust offers various green services such as the visualization of environmental data collected by citizen, the alert services, the ability to download data, the forum for sharing ideas and best practices in terms of eco-responsible behaviors. MyGreenServices provides access to citizen measures (stations and electric vehicles) for any registered user. Moreover, citizens who host a station can trace the time history of the data sensed. The priority was to provide to users all the IoT data by them. Two ways to represent data have been chosen as shown in Figure 1 :

- The use of maps with measures coming from environmental sensors and based on a colour scale indication;
- The pollution curves that support the cartography and allow the access to the detailed data for the user.

A pollution alert service has been created considering two points of view:

- The first consists of localising a person (with his agreement) and indicating via email or text message the passage through a polluted area;
- The second allow the user to define an area to follow and the user will be advised of pollution alerts for the area by email or text message.

An important effort has been done in designing, testing and improving user interfaces based on pre-test with the usability testing software named Morae and experiments in real situations.

Two experiments have been carried out in February and in June 2013, with the aim to test the platform MyGreenServices by two user profiles (consumers and producers of data) and to measure User experience. The aim of the experiments is to assess the user experience and experiential learning related to MyGreenServices; this includes experience related to the IoT devices, to the measures and services as well as air quality awareness and behaviour changes monitoring. See Section 6.5.3) for more details on the used model and measurement methodology.

For supporting Citizen Sensing, we elaborated IoT installation guides for our three Pollution stations (based on user feedbacks): Pollux station for dust from CKAB ⁷, Azimut stations for Ozone and Nitrogen dioxide from Azimut Monitoring ⁸ and AxISbox stations for dust (Inria Cf. Section 6.5.2).

In order to ensure a proper data analysis, log and usage analytics were structured and gathered in an admin tool designed by the AxIS team at Inria. This tool is a component of the MyGreenServices portal.

6.5.2. AxISbox, a Prototype of a Low-Cost Dust Arduino-based Station

Participant: Guillaume Pilot.

In order to provide more citizen sensors during our Elliot experiments, we developed a first prototype of a new low cost dust (PM10) station (with Rasburry and Arduino) called AxISbox (cf. Figure 2) which we tested for research purposes. This prototype was validated during the second ELLIOT experiment in June.

6.5.3. Modelling and Measuring User Experience for Green IoT-based Services

Participants: Brigitte Trousse, Anne-Laure Negri, Caroline Tiffon, Xavier Augros, Guillaume Pilot.

⁷CKAB URL: <http://ckab.com/polluxnz-city>

⁸Azimut Monitoring URL: <http://www.azimut-monitoring.com/>



Figure 1. MyGreenServices Platform



Figure 2. Citizen sensors: Pollux station, AxISbox and Azimut mobile station

In accordance with the overall objective of MyGreenServices, we provided an UX modelling and measurement methodology for Green IoT-based services we applied on MyGreenServices. In our ELLIoT context, we focused on the level of awareness/experiential learning raised after usage of MyGreenServices (awareness pollution, awareness of citizen dissemination and change of behaviors), the ease of use and diffusion aspects (as being a tool provided to the citizen). Two objects of the learning were considered: IoT via myGreenServices portal and Air quality. We used a differential between a pre-profile and post-profile. Our UX methodology in the context of ELLIOT project is lying on the five steps we applied on the two versions of MyGreenServices:

- Instantiation of the holistic UX model elaborated within ELLIOT [63] (cf. the first three columns in Figure 3),
- Choice of types of UX momentary, episodic, cumulative) depending on the moment of the measurement (cf. Figure 4),
- Identification of relevant data to be collected and UX indicators (cf. the last two columns in Figure 3),
- Definition of UX metrics for indicators and rules (see Section 6.5.4 for the example of the Usefulness property),
- and finally data pre-processing and UX indicators/properties computation (via for some properties FocusLab 6.6).



Figure 3. MyGreenServices UX Model

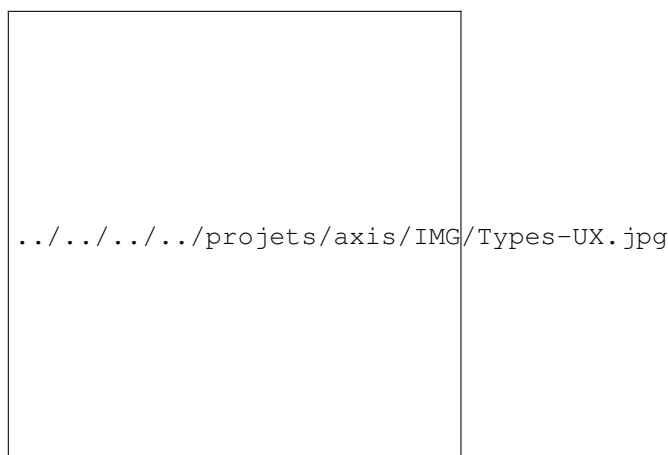


Figure 4. UX Types extracted from [70]

The two experiments clearly indicate both good results in terms of user experience with better result for the second experiment due to the improvement of MyGreenServices (v2) and better community management. A comparative analysis has been made for our two experiments, showing better quantitative value of UX indicators for the second version which was based on User feedback.

6.5.4. Evaluating User Behaviour Changes For MyGreenServices Usefulness Measurement

Participants: Brigitte Trousse, Yves Lechevallier, Xavier Augros, Caroline Tiffon.

The Usefulness UX property of our UX model [38] is calculated by aggregating the analysis of two questions related to a change of behaviours during (4 times) and/or after the experiment in terms of: transportation, aeration, outgoing, sport, aeration or others. We used the web service MNDClustering_Sequence (based on our MND clustering method [45]) to classify the answers to these questions and to provide a sequence of clusters by each user. See Section 6.6.2 related to this new web service.

A data table was built with all the answers for each (user, timestamp) and is analyzed to generate a partition in 3 clusters for the experiment by calling the Focuslab MND webservice (cf. Section 6.2.5) which has been improved this year. The Output via MNDClusterSequence web service is a csv data file with for each user the sequence of 5 clusters obtained during the experiment.

Then we identified the users having changed their behaviour. We use the following UX rules to conclude on this property:

- If % users declaring a change of behaviour $> 5\%$ then high
- If % users declaring a change of behaviour $< 5\%$ and $> 1\%$ then medium
- If % users declaring a change of behaviour $< 1\%$ then low

The result is "high" related to our two experiments. Note that other questions related to the usefulness of some MyGreenServices functionalities (alerts, forum, data synthesis, etc.) could be integrated in a more global rule for Usefulness.

6.5.5. Persuasive Technologies in Energy Economy

Participants: Bernard Senach, Anne-Laure Negri.

The ECOFFICES project [51] was for AxIS project team our first step towards eco-behaviour study. This research was complemented in 2012 with a literature review aiming at a deeper understanding of breaks and levers to eco behavior adoption. The work in this topic lead to a presentation⁹ in the mobility context during the GreenCode Forum (see the video on YouTube) and to an internal seminar for Axis members. A draft of an Inria research report on this topic has been started.

The two research lines "Energy Economy" and "Persuasive Technology" have been merged and an analysis of the Ecoffices challenge has been engaged in the light of works in the fields of Persuasive Technologies and Game Design. In this analysis, the Ecoffices Energy challenge is considered as an hybrid system combining gamification and persuasive principles. Using available models of each field, the experimental device used in the Ecoffices project is deconstructed and evaluated. The persuasive quality analysis relies on the Persuasive System Design model [62]. Concerning the gaming quality of Ecoffices, a first model (Octalysis <http://www.yukaichou.com/gamification-examples/octalysis-complete-gamification-framework/>) was discarded and we are now using the gamification principles from the literature for the analysis [76].

At the end of 2012, we joined the work group PISTIL (Persuasive Interaction for SusTainabilLity) and engaged several actions within this group and two papers are planned for the JIPS 2014 Special Issues on Persuasive Technologies¹⁰: one on an analysis of the ECOFFICES challenge (under writing) and another on the design and evaluation of persuasive systems.

6.5.6. *Persuasive Technologies in Green Services*

Participants: Brigitte Trousse, Anne-Laure Negri, Mylène Leitzelman, Florian Bonacina, Caroline Tiffon.

The ELLIOT project was for AxIS project team our second step towards eco-behaviour study. It provided us a very rich context to study behaviour changes related to pollution awareness. Our experimental results showed a very promising tendency in terms of user behaviour changes and the impact of MyGreenServices on leading user eco-behaviours [38].

Persuasive technologies and gamification were used in the context of green Services use case. A specific focus was on gamification for the two customised Ideastream-based tools we developed for the co-creation step and mainly for the one used inside MyGreenServices platform (see Figure 5).

6.6. FocusLab Platform

6.6.1. *New Graphical Charter and New Functionalities*

Participants: Xavier Augros, Florian Bonacina, Brigitte Trousse.

This year we implemented a new version of the Focuslab platform (v1.3) (<http://focuslab.inria.fr>) with a new graphical charter, the addition of the documentation part (books, articles, thesis, reports, etc.) and new functionalities such as cross references between the hardware/software parts with the documentation part, the opportunity of reserving hardware, hardware+software or documentation and a new administration interface. This new version has been tested internally in the team at the end of the year.

6.6.2. *FocusLab Generic Web Service: MNDCluster_Sequence*

Participants: Xavier Augros, Yves Lechevallier, Brigitte Trousse.

This year for Elliot purposes, we built a new FocusLab generic Web Service called MNDCluster-Sequence. This web service uses the new release of MND clustering method [80] (cf. Section 6.2.5) which computes the best partition based on all data for each (user, timestamp). Then it builds for each user the sequence of 5 clusters taking into account the five user time stamp in our case. The resulting sequences are then added for each user as new qualified data in the dataset of Green Services.

This web service is added to those already integrated in FocusLab (See for more details our 2012 activity report <http://raweb.inria.fr/rapportsactivite/RA2012/axis/uid116.html>)

⁹URL: http://www-sop.inria.fr/axis/papers/2012/GreenCode_2012

¹⁰On-line journal : Journal d' Interaction Personne-Système, Journal of "Association Francophone d'Interaction Homme-Machine".



Figure 5. "Gamified Forum" page (including AxISbox)

GALAAD Project-Team

6. New Results

6.1. Algebraic representations for geometric modeling

6.1.1. *Fitting ideals and multiple-points of surface parameterizations*

Participant: Laurent Busé.

Parameterized algebraic surfaces are ubiquitous in geometric modeling and the determination of their singular loci is an important problem. Given a birational parameterization ϕ from \mathbb{P}^2 to \mathbb{P}^3 of a rational algebraic surface \mathcal{S} , the purpose of this work is to investigate the sets of points on \mathcal{S} whose preimage consists in k or more points, counting multiplicity. In collaboration with Nicolas Botbol (University of Buenos Aires) and Marc Chardin (UMPC), we prove that they can be described in terms of Fitting ideals of some graded parts of the symmetric algebra associated to the parameterization ϕ . More precisely, we show that the drop of rank of a certain elimination matrix $M(\phi)$ at a given point $P \in \mathbb{P}^3$ is in relation with the fiber of the graph of ϕ over P . Thus, the Fitting ideals attached to $M(\phi)$ provide a filtration of the surface which is in correspondence with the degree and the dimension of the fibers of the graph of the parameterization ϕ . This property is linked with the double-point formulas that have been extensively studied in the field of intersection theory for finite maps.

This work has been accepted for presentation at the international conference MEGA 2013 and is submitted for publication [33].

6.1.2. *Discriminant of a homogeneous and symmetric polynomial*

Participant: Laurent Busé.

Polynomial algebra offers a standard approach to handle several problems in geometric modeling. A key tool is the discriminant of a well-constrained system of polynomial equations, which expresses the existence of a multiple root. In this work the factorization of a single homogeneous and symmetric polynomial is investigated. Indeed, in this setting the discriminant possesses a lot of symmetries and all of these symmetries produce an independent factor of the global discriminant. The two difficult points here are to prove that each of these factors are irreducible over a nice base ring and to determine its multiplicity in the factorization of the discriminant. This work, in collaboration with Anna Karasoulou (University of Athens) is still under progress.

6.1.3. *On the cactus rank of cubic forms*

In [14], we prove that the smallest degree of an apolar 0-dimensional scheme of a general cubic form in $n + 1$ variables is at most $2n + 2$, when $n \geq 8$, and therefore smaller than the rank of the form. For the general reducible cubic form the smallest degree of an apolar subscheme is $n + 2$, while the rank is at least $2n$.

This is a work done by Alessandra Bernardi when she was post-doctorate for DECONSTRUCT IEF project, in collaboration with Kristian Ranestad (University of Oslo).

6.1.4. *Grassmann secants and linear systems of tensors*

For any irreducible non-degenerate variety $X \subset \mathbb{P}^r$, we relate in [11] the dimension of the s -th secant varieties of the Segre embedding of $\mathbb{P}^k \times X$ to the dimension of the (k, s) -Grassmann secant variety $GS_X(k, s)$ of X . We also give a criterion for the s -identifiability of X .

This is a work done by Alessandra Bernardi when she was post-doctorate for DECONSTRUCT IEF project, in collaboration with Edoardo Ballico (University of Trento), Maria Virginia Catalisano (DIPTM, Genova), Luca Chiantini (University of Sienna).

6.1.5. *Optimal analysis-aware parameterization of computational domain in 3D isogeometric analysis*

Participants: André Galligo, Bernard Mourrain.

In isogeometric analysis framework, computational domain is exactly described using the same representation as that employed in the CAD process. For a CAD object, we can construct various computational domain with same shape but with different parameterization. One basic requirement is that the resulting parameterization should have no self-intersections. In [27], a linear and easy-to-check sufficient condition for injectivity of trivariate B-spline parameterization is proposed. By an example of 3D thermal conduction problem, we show that different parameterization of computational domain has different impact on the simulation result and efficiency in isogeometric analysis. For problems with exact solutions, we propose a shape optimization method to obtain optimal parameterization of computational domain. The proposed injective condition is used to check the injectivity of initial trivariate B-spline parameterization constructed by discrete Coons volume method, which is the generalization of discrete Coons patch method. Several examples and comparisons are presented to show the effectiveness of the proposed method. Compared with the initial parameterization during refinement, the optimal parameterization can achieve the same accuracy but with less degrees of freedom.

This is a joint work with Régis Duvigneau (Inria, EPI OPALE) and Xu Gang (College of computer - Hangzhou Dianzi University, China).

6.1.6. Constructing analysis-suitable parameterization of computational domain from CAD boundary by variational harmonic method

Participants: André Galligo, Bernard Mourrain.

In isogeometric analysis, parameterization of computational domain has great effects as mesh generation in finite element analysis. In the paper [26], based on the concept of harmonic mapping from the computational domain to parametric domain, a variational harmonic approach is proposed to construct analysis-suitable parameterization of computational domain from CAD boundary for 2D and 3D isogeometric applications. Different from the previous elliptic mesh generation method in finite element analysis, the proposed method focuses on isogeometric version, and converts the elliptic PDE into a nonlinear optimization problem, in which a regular term is integrated into the optimization formulation to achieve more uniform and orthogonal iso-parametric structure near convex (concave) parts of the boundary. Several examples are presented to show the efficiency of the proposed method in 2D and 3D isogeometric analysis.

This is a joint work with Régis Duvigneau (Inria, EPI OPALE) and Xu Gang (College of computer - Hangzhou Dianzi University, China).

6.1.7. Spline Spaces over Quadrangle Meshes with Complex Topologies

Participants: Meng Wu, André Galligo, Bernard Mourrain.

We study a new type of spline functions defined over a rectangular mesh equipped with an equivalence relation, in such a way that physical spaces with a complex topology can be represented as an homomorphic image of such meshes. We provide general definitions, a dimension formula for a subclass of these spline spaces, an explicit construction of their bases and also a process for local refinement. These developments, motivated by plane curvilinear mesh constructions are illustrated on several parametrization problems. Our main target in these constructions is to approximate isobaric lines of magnetic fields encountered in MHD (Magnetohydrodynamics) simulation for Tokamaks. Their particularity is that one of the isobaric curve has a node singularity.

This work is done in collaboration with Boniface Nkonga (Inria, EPI CASTOR and University of Nice).

6.1.8. Lagrangian Curves in Affine Symplectic 4-space

Participant: Evelyne Hubert.

Lagrangian curves in 4-space entertain intriguing relationships with second order deformation of plane curves under the special affine group and null curves in a 3-dimensional Lorentzian space form. In [39] we provide a natural affine symplectic frame for Lagrangian curves. It allows us to classify Lagrangian curves with constant symplectic curvatures, to construct a class of Lagrangian tori and determine Lagrangian geodesics.

This is joint work with Emilio Musso, Dipartimento di Scienze Matematiche, Politecnico de Torino (Italy).

6.2. Algebraic algorithms for geometric computing

6.2.1. *Implicit matrix representations of rational Bézier curves and surfaces*

Participant: Laurent Busé.

In this work, we introduce and study a new implicit representation of rational Bézier curves and surfaces in the 3-dimensional space. Given such a curve or surface, this representation consists of a matrix whose entries depend on the space variables and whose rank drops exactly on this curve or surface. Our approach can be seen as an extension of the moving lines implicitization method introduced by Sederberg, from non-singular matrices to the more general context of singular matrices. First, we describe the construction of these new implicit matrix representations and their main geometric properties, in particular their ability to solve efficiently the inversion problem. Second, we show that these implicitization matrices adapt geometric problems, such as intersection problems, to the powerful tools of numerical linear algebra, in particular to one of the most important: the singular value decomposition. So, from the singular values of a given implicit matrix representation, we introduce a real evaluation function. We show that the variation of this function is qualitatively comparable to the Euclidean distance function. As an interesting consequence, we obtain a new determinantal formula for implicitizing a rational space curve or surface over the field of real numbers. Then, we show that implicit matrix representations can be used with numerical computations, in particular there is no need for symbolic computations to use them. We give some rigorous results explaining the numerical stability that we have observed in our experiments. We end the paper with a short illustration on ray tracing of parameterized surfaces.

This work has been accepted for presentation and publication at the SIAM conference on Geometric and Physical Modeling 2013 (Denver, USA, Nov. 11-14) [15]. It has been awarded the best paper price, 1st place.

6.2.2. *Superfast solution of Toeplitz systems based on syzygy reduction*

Participant: Bernard Mourrain.

In [22], we present a new superfast algorithm for solving Toeplitz systems. This algorithm is based on a relation between the solution of such problems and syzygies of polynomials or moving lines. We show an explicit connection between the generators of a Toeplitz matrix and the generators of the corresponding module of syzygies. We show that this module is generated by two elements and the solution of a Toeplitz system $Tu = g$ can be reinterpreted as the remainder of a vector depending on g , by these two generators. We obtain these generators and this remainder with computational complexity $O(n \log^2 n)$ for a Toeplitz matrix of size $n \times n$.

This is a joint work with Houssam Khalil (Université Claude Bernard - Lyon I) and Michelle Schatzman (Institut Camille Jordan, Lyon).

6.2.3. *Budan Tables of Real Univariate Polynomials*

Participant: André Galligo.

The Budan table of f collects the signs of the iterated derivative of f . We revisit the classical Budan-Fourier theorem for a univariate real polynomial f and establish a new connexity property of its Budan table. In [18], we use this property to characterize the virtual roots of f , (introduced by Gonzales-Vega, Lombardi, Mahe in 1998); they are continuous functions of the coefficients of f . We also consider a property (P) of a polynomial f , which is generically satisfied, it eases the topological-combinatorial description and study of the Budan tables. A natural extension of the information collected by the virtual roots provides alternative representations of (P)-polynomials; while an attached tree structure allows a stratification of the space of (P)-polynomials.

6.2.4. *A polynomial approach for extracting the extrema of a spherical function and its application in diffusion MRI*

Participant: Bernard Mourrain.

Antipodally symmetric spherical functions play a pivotal role in diffusion MRI (Magnetic Resonance Imaging) in representing sub-voxel-resolution microstructural information of the underlying tissue. This information is described by the geometry of the spherical function. In [20], we propose a method to automatically compute all the extrema of a spherical function. We then classify the extrema as maxima, minima and saddle-points to identify the maxima. We take advantage of the fact that a spherical function can be described equivalently in the spherical harmonic (SH) basis, in the symmetric tensor (ST) basis constrained to the sphere, and in the homogeneous polynomial (HP) basis constrained to the sphere. We extract the extrema of the spherical function by computing the stationary points of its constrained HP representation. Instead of using traditional optimization approaches, which are inherently local and require exhaustive search or re-initializations to locate multiple extrema, we use a novel polynomial system solver which analytically brackets all the extrema and refines them numerically, thus missing none and achieving high precision. To illustrate our approach we consider the Orientation Distribution Function (ODF). In diffusion MRI the ODF is a spherical function which represents a state-of-the-art reconstruction algorithm whose maxima are aligned with the dominant fiber bundles. It is, therefore, vital to correctly compute these maxima to detect the fiber bundle directions. To demonstrate the potential of the proposed polynomial approach we compute the extrema of the ODF to extract all its maxima. This polynomial approach is, however, not dependent on the ODF and the framework presented in this paper can be applied to any spherical function described in either the SH basis, ST basis or the HP basis.

This is a joint work with Aurobrata Ghosh (Inria, EPI ATHENA), Elias Tsigaridas (Inria, EPI POLSYS), Rachid Deriche (Inria, EPI ATHENA).

6.2.5. *The geometry of sound-source localization using non-coplanar microphone arrays*

The paper [29] addresses the task of sound-source localization from time delay estimates using arbitrarily shaped non-coplanar microphone arrays. We fully exploit the direct path propagation model and our contribution is threefold: we provide a necessary and sufficient condition for a set of time delays to correspond to a sound source position, a proof of the uniqueness of this position, and a localization mapping to retrieve it. The time delay estimation task is casted into a non-linear multivariate optimization problem constrained by necessary and sufficient conditions on time delays. Two global optimization techniques to estimate time delays and localize the sound source are investigated. We report an extensive set of experiments and comparisons with state-of-the-art methods on simulated and real data in the presence of noise and reverberations.

This is a joint work with Xavier Alameda-Pineda (Inria, EPI PERCEPTION) and Radu Horaud (Inria, EPI PERCEPTION).

6.2.6. *Rational Invariants of a Group Action*

Participant: Evelyne Hubert.

The article [28] is based on introductory lectures delivered at the Journées Nationales de Calcul Formel that took place at the Centre International de Recherche en Mathématiques (2013) in Marseille. We introduce basic notions on algebraic group actions and their invariants. Based on geometric considerations, we present algebraic constructions for a generating set of rational invariants. In particular the use of sections and quasi-sections contribute to increased efficiency and reduced output size. The notion of sections is refined compared to the cross-sections used in [9].

6.2.7. *Rational Invariants of Finite Abelian groups*

Participant: Evelyne Hubert.

In [36] we investigate the field of rational invariants of the linear action of a finite abelian group in the non modular case. By diagonalization, the group is accurately described by an integer matrix of exponents. We make use of linear algebra to compute a minimal generating set of invariants and the substitution to rewrite any invariant in terms of this generating set. We show that the generating set can be chosen to consist of polynomial invariants. As an application, we provide a symmetry reduction scheme for polynomial systems the solution set of which are invariant by the group action.

This is joint work with George Labahn, University of Waterloo, Ontario (Canada).

6.2.8. *Exact relaxation for polynomial optimization on semi-algebraic sets*

Participants: Marta Abril Bucero, Bernard Mourrain.

In [31], we study the problem of computing by relaxation hierarchies the infimum of a real polynomial function f on a closed basic semialgebraic set S and the points where this infimum is reached, if they exist. We show that when the infimum is reached, a relaxation hierarchy constructed from the Karush-Kuhn-Tucker ideal is always exact and that the vanishing ideal of the KKT minimizer points is generated by the kernel of the associated moment matrix in that degree, even if this ideal is not zero-dimensional. We also show that this relaxation allows to detect when there is no KKT minimizer. We prove that the exactness of the relaxation depends only on the real points which satisfy these constraints. This exploits representations of positive polynomials as elements of the preordering modulo the KKT ideal, which only involves polynomials in the initial set of variables. The approach provides a uniform treatment of different optimization problems considered previously. Applications to global optimization, optimization on semialgebraic sets defined by regular sets of constraints, optimization on finite semialgebraic sets, real radical computation are given.

6.3. Symbolic-Numeric Analysis

6.3.1. *Numerical Reconstruction of Convex Polytopes from Directional Moments*

Participants: Mathieu Collowald, Evelyne Hubert.

In [35] we address the reconstruction of convex polytopes, in any dimension n , from the knowledge of a finite set of directional moments of the shape. Starting with the formula relating the projection of the vertices to the directional moments, we employ established numerical algorithms for generalized eigenvalues and interval interpolation to recover the coordinates of the vertices. We perform the reconstruction of a diamond cut using our novel method.

This is joint work with Annie Cuyt, Wen-Shin Lee and Oliver Salazar Celis from University of Antwerp (Belgium).

6.3.2. *Bulbous Bow Shape Optimization*

Participant: Bernard Mourrain.

The aim of the work [30] is to prove the usefulness of a bulbous bow for a fishing vessel, in terms of drag reduction, using an automated shape optimization procedure including hydrodynamic simulations. A bulbous bow is an appendage that is known to reduce the drag, thanks to its influence on the bow wave system. However, the definition of the geometrical parameters of the bulb, such as its length and thickness, is not intuitive, as both parameters are coupled with regards to their influence on the final drag. Therefore, we propose to use an automated shape optimization procedure, based on a high-fidelity flow solver, a surrogate model-based optimizer and a CAD-based geometrical model, to derive the characteristics of the bow geometry allowing to maximize the achievable drag reduction. The numerical tools are first presented, and then applied to the optimization of a bow shape for a real fishing vessel, in order to determine the optimal length and thickness of the bow for drag reduction purpose.

This is a joint work with Louis Blanchard and Régis Duvigneau (Inria, EPI OPALE), Elisa Berrini (MyCFD), Yann Roux (K-Epsilon) Eric Jean (Jean & Frasca Design).

AOSTE Project-Team

6. New Results

6.1. Process Networks with routing for parallel architectures

Participants: Robert de Simone, Emilien Kofman, Jean-Vivien Millo.

In the past we developed a dedicated Process Network (PN) formalism with explicit static switching/routing schemes for data flow. This year we considered the practical use of our formalism to model data-streams in specific applicative contexts.

In a first direction we considered the case of stencil algorithms, usually modeled with cellular automata (CA) (as in heat or gas propagation models for instance). In that case, the application itself is modeled in a way strongly similar to a physical architecture consisting of a regular mesh/array of parallel processors (MPPA). Mapping can seem to be straightforward then, *safe that* the neighborhood and connection topology may differ from the CA model to the MPPA. Our results consider efficient routing and propagation schemes on a given MPPA interconnect fabric, so as to match all-to-all broadcast patterns up to a given distance (on the CA topology). They are described in [20], and were implemented on Kalray MPPA256 prototype architecture.

A similar modeling effort was conducted, this time on FFT algorithm models (again described as parallel pipe-lined tasks). Again switching/routing schemes were provided in our formal PN model to map the virtual logical dependences onto concrete connection patterns in a MPPA256 model. This was the subject of Emilien Kofman internship, of which preliminary results were presented in a junior workshop [36].

6.2. Formal analysis of MARTE Time Model and CCSL

Participants: Frédéric Mallet, Robert de Simone, Yuliia Romenska, Jean-Vivien Millo, Ling Yin.

We have worked on building analysis methods and tools for running exhaustive analyses on MARTE/CCSL specifications. This was done by endowing CCSL with a State-Based semantics [51]. Each operator is described as a boolean state machine, some operators require an infinite number of states. When this is the case we rely on a lazy representation technique to capture symbolically the infinite number of states [45]. The semantics of a CCSL specification is then expressed as the synchronized product of the (infinite) state machines for each operator. Even though the operators are infinite, their composition can sometimes be bounded. When the synchronized product has only a finite number of reachable states, it is said to be safe. We have identified a set of representative and frequently used examples where this is the case [38]. When the product is not finite, our (semi-)algorithm to build the product does not terminate, therefore it is important to be able to know in advance whether or not the product is safe. We have thus proposed an algorithm to decide whether a CCSL specification is safe [37]. It relies on an intermediate representation called Clock Causality Graph and uses results from marked graph theory.

Building the product for a CCSL specification is exponential in the number of clocks and is not practical for large specifications. So, to avoid building explicitly the product we have proposed another technique to explore symbolically the state-space of a CCSL specification [49]. This relies on a liveness condition where no conflict may prevent an infinite clock from ticking infinitely often. Branches that may lead to states where an infinite clock dies are pruned by a fix-point algorithm.

These two solutions focus on the logical and discrete aspects of MARTE/CCSL, which was devised to unify logical and physical time constraints. An attempt to support verification of the physical time constraints of MARTE/CCSL was conducted through the use of UppAal timed automata and model-checker [46]. The proposed technique combines the logical clocks of CCSL with the real-valued clocks of timed automata. Synchronous/Polychronous aspects are solved with TimeSquare 5.1 while the UppAal model-checker is used to explore the space derived from the real-valued clocks.

6.3. Logical time in Model-Driven Engineering of embedded systems

Participants: Frédéric Mallet, Julien Deantoni, Robert de Simone, Marie-Agnès Peraldi Frati, Matias Varalarsen, Arda Goknil.

In the context of our approach based on logical time to specify causalities and synchronizations on models, 3.2, we developed an extension of the OMG OCL Object Constraint Language. Named ECL (Event Constraint Language) it provides such specifications of causality and synchronization at syntactic language level, which enabled then automatic generation of semantic logical time constraints for any model that conforms the language.

This year, we extended to a new challenge, using logical time constraints to coordinate models of *several distinct* languages used jointly for a large heterogeneous system description. This work is reported in [25], [52].

It was illustrated in practice in the automotive domain by coordinating together the Timed Augmented Description Language (TADL2) and the EAST-ADL language [34], [32] (the formalisms are rather similar, but still with clear distinctions at places).

Finally, we proposed a pattern to assemble the (possibly concurrent) semantics of a language associating our logical time constraints (based on pure clocks) with a syntactic action language (providing behavior content). By reifying events and constraints, this specification of the semantics is amenable to its composition [25]. Such approach has been, again, recently used for a first attempt to coordinate distinct behavioral models [47].

As part of our collaboration in the DAESD associated-team with ECNU Shone-SEI in Shanghai we studied the coupling of discrete-logical with continuous-physical time models, ending with a proposal of Hybrid MARTE statecharts [19] specified in a style much like a combinaison of MARTE state diagrams and timed automata.

In another setting we presented a new model of scenarios [21], dedicated to the specification and verification of system behaviours in the context of software product lines (SPL). The formalism uses the logical time modeling approach, with a strong link to synchronous semantics. We draw our inspiration from some techniques that are mostly used in the hardware community, and we show how they could be applied to the verification of software components and product line variability. We point out the benefits of synchronous languages and models to bridge the gap between both worlds.

6.4. Multiview modeling and power intent in Systems-on-chip

Participants: Carlos Gomez Cardenas, Ameni Khecharem, Emilien Kofman, Frédéric Mallet, Julien Deantoni, Robert de Simone.

Power models for embedded architectures (where power consumption is highly constrained) provide an ideal example of a non-functional modeling framework with strong interactions with the functional and performance models: more speed in computation comes at the cost of larger energy consumption. There was also a demand for a framework allowing combinaison of models, each representing a distinct view of the system. We demonstrated as part of the HeLP ANR project 8.2.1.1, followed by the newly started HOPE ANR project 8.2.1.2, how such multiview modeling could be done, and how it could be connected down to more concrete simulation code or model, as in SystemC, Docea Power AcePlorer, or Scilab code. The multiview modeling applied to power intent and power managers was described in [35], and led to the PhD defense of Carlos Gomez Cardenas in December 2013 [16].

6.5. Performance variability analysis on manycore architectures

Participants: Sid Touati, Amin Oueslati, Franco Pesarini, Robert de Simone, Emilien Kofman.

In the context of the collaboration with Kalray (see 7.1.1), we conducted a systematic benchmarking campaign to test the stability (or low variability) of the performances of the MPPA256 prototype manycore processor. We first addressed issues of memory access and network latency, then programmed a distributed version of the classical ALL_PAIRS_SHORTEST_PATH parallel algorithm with an hybrid OpenMP/MPI style. This was the objectif of Amin Oueslati Master2 internship. Results were encouraging, and showed stability of performance over a large set of runs.

This work is currently extended during the International Internship grant of Franco Pescarini. Specific on-chip communication modes offered by the MPPA256 processor (namely *portal* and *channel* communication modes) are being extensively benchmarked. Results show time predictability on the case of light on-chip communication traffic, but stability gets degraded as performance decreases in presence of heavy traffic and congestion (various runs show quite different execution time).

In another effort we conducted during the internship period of Emilien Kofman an experiment on MPPA256 quite similar to the work conducted as part of the collaboration with Kontron (see 7.1.3), exploring various mapping options of FFT algorithm variants, with the goal of figuring how to best map (in the future) several such algorithms onto the computation fabric of the many-cores available.

6.6. Off-line (static) mapping of real-time applications onto NoC-based many-cores

Participants: Thomas Carle, Manel Djemal, Dumitru Potop Butucaru, Robert de Simone, Zhen Zhang.

Modern computer architectures are increasingly relying on multi-processor systems-on-chips (MPSoCs, also called chip-multiprocessors), with data transfers between cores and RAM banks managed by on-chip networks (NoCs). This reflects in part a convergence between embedded, general-purpose PC, and high-performance computing (HPC) architecture designs. In past years we have identified and compared the hardware mechanisms supporting precise timing analysis and efficient resource allocation in existing NoCs. We determined that the NoC should ideally provide the means of enforcing a global communications schedule that is computed off-line and which is synchronized with the scheduling of computations on CPU cores (and we have built such a NoC).

This year we have focused on the problem of mapping applications onto NoC-based MPSoCs (discussed in this section) and on the associated problem of timing analysis of the resulting parallel implementations (discussed in section 6.7). On-chip networks used in MPSoCs pose significant challenges to both on-line and off-line real-time scheduling approaches. They have large numbers of potential contention points, have limited internal buffering capabilities, and network control operates at the scale of small data packets. Therefore, precise schedulability analysis requires scalable algorithms working on hardware models with a level of detail that is unprecedented in real-time scheduling.

We considered an off-line scheduling approach, and we targeted massively parallel processor arrays (MPPAs), which are MPSoCs with large numbers (hundreds) of processing cores. We proposed a novel allocation and scheduling method capable of synthesizing such global computation and communication schedules covering all the execution, communication, and memory resources in an MPPA. To allow an efficient use of the hardware resources, our method takes into account the specificities of MPPA hardware and implements advanced scheduling techniques such as pre-computed preemption of data transmissions and pipelined scheduling.

Our method has been implemented within the Lopht tool presented in section 5.4, and first results are presented in [54]. One of the objectives of the collaboration with Kalray SA is the evaluation of the possibility of porting Lopht onto the Kalray MPPA platform.

6.7. WCET estimation for parallel code

Participant: Dumitru Potop Butucaru.

This is joint work with Isabelle Puaut, Inria, EPI ALF.

Classical timing analysis techniques for parallel code isolate micro-architecture analysis from the analysis of synchronizations between cores by performing them in two separate analysis phases (WCET – worst-case execution time – and WCRT – worst-case response time analyses). This isolation has its advantages, such as a reduction of the complexity of each analysis phase, and a separation of concerns that facilitates the development of analysis tools. But isolation also has a major drawback: a loss in precision which can be significant. To consider only one aspect, to be safe the WCET analysis of each synchronization-free sequential code region has to consider an undetermined micro-architecture state. This may result in overestimated WCETs, and consequently on pessimistic execution time bounds for the whole parallel application.

The contribution of this work [56], [44] is an *integrated* WCET analysis approach that considers at the same time micro-architectural information and the synchronizations between cores. This is achieved by extending a state-of-the-art WCET estimation technique and tool to manage synchronizations and communications between the sequential threads running on the different cores. The benefits of the proposed method are twofold. On the one hand, the micro-architectural state is not lost between synchronization-free code regions running on the same core, which results in tighter execution time estimates. On the other hand, only one tool is required for the temporal validation of the parallel application, which reduces the complexity of the timing validation toolchain.

Such a holistic approach is made possible by the use of deterministic and composable software and hardware architectures (many-cores with no cache sharing and time-predictable interconnect, static assignment of the code and data to the memory banks). Such code can be written by hand or automatically synthesized using the Lopht tool 5.4 or other automatic parallelization techniques.

6.8. Real-time scheduling and code generation for time-triggered platforms

Participants: Thomas Carle, Raul Gorcitz, Dumitru Potop Butucaru, Yves Sorel.

We have continued this year the work on real-time scheduling and code generation for time-triggered platforms. This work was mainly carried out as part of a bilateral collaboration with Astrium Space Transportation (now part of Airbus Defence and Space), which co-funded with the CNES the post-doctorate of Raul Gorcitz (started in September).

The work focused this year on the improvement of the real-time scheduling and code generation (the PhD work of T. Carle), and on determining their adequacy to Astrium's industrial needs (the post-doc of Raul Gorcitz). We have improved our specification, mapping, and code generation technique at all levels. We have extended the Lopht tool to allow automatic mapping and code generation for single-processor and multi-processor partitioned targets (using an ARINC 653-compliant OS).

6.9. Uniprocessor Real-Time Scheduling

Participants: Yves Sorel, Falou Ndoeye, Daniel de Rauglaudre.

6.9.1. Formal Proofs of Uniprocessor Real-Time Scheduling Theorems

We continued writing a monograph about three formal proofs, done in 2011/2012, in Coq on scheduling of fixed priority real-time preemptive tasks: one about the scheduling conditions of strict periodicity and two about the worst response time in the case of preemptive deadline monotonic scheduling. This document contains about 120 pages for the moment.

6.9.2. Real-Time Scheduling with Exact Preemption Cost

We proposed a new schedulability condition for dependent tasks executed on a uniprocessor which takes into account the exact preemption cost. Unlike the work presented in [10] which achieves that goal only for fixed priority tasks, our schedulability condition considers fixed as well as dynamic priorities tasks. Thus, we can overcome priority inversions involved by data dependent tasks. The schedulability analysis based on this schedulability condition led to an off-line scheduler [42] described by a scheduling table. Therefore, we have proposed an on-line time-trigger scheduler which implements this scheduling table. Compared to classical on-line schedulers, the proposed approach has two benefits. On the one hand the cost of the task selection amounts only to read the task to be executed in the scheduling table built off-line, rather than using on-line a scheduling algorithm like RM, DM, EDF, etc. On the other hand this cost is fixed since it does not depend on the number of ready tasks. In addition, with our on-line scheduler we do not need to synchronize, on-line, the utilization of the shared memory data, due to dependences, because this synchronization is performed during the off-line schedulability analysis.

6.10. Multiprocessor Real-Time Scheduling

Participants: Yves Sorel, Laurent George, Dumitru Potop-Butucaru, Falou Ndoye, Aderraouf Benyahia, Cécile Stentzel, Meriem Zidouni.

6.10.1. Multiprocessor Partitioned Scheduling with Exact Preemption Cost

We finalized the work started in previous years on multiprocessor scheduling of preemptive independent real-time tasks with exact preemption cost [43].

This year we proposed a heuristic for the multiprocessor scheduling of preemptive dependent real-time tasks with exact preemption cost. We chose the partitioned approach that avoids migration of tasks and allows the utilization of the uniprocessor schedulability condition, previously proposed, that takes into account the exact preemption cost. In addition, this schedulability condition takes into account the inter-processor communications and guarantees that no data is lost. The result of such an off-line scheduling provided by the heuristic, is a scheduling table for every processor which includes also inter-processor communication tasks. We compared our multiprocessor scheduling heuristic with a Branch & Bound exact algorithm using the same schedulability condition. Our heuristic provides similar results and is very much faster.

6.10.2. Multiprocessor Semi-Partitioned Mixed Criticality Scheduling

We mainly focused on the mixed criticality scheduling problem applied to semi-partitioned scheduling considering a static pattern of migration for jobs. We have studied this problem in the context of Mixed Criticality (MC) scheduling, a promising approach that can be used to take into account applications of different criticality levels on the same platform. The goal of MC approach is to better utilize computing resources by allowing low criticality tasks to execute in conjunction with high criticality tasks when the system criticality is not high.

6.10.3. Gateway with Modeling Languages for Certified Code Generation

This work was carried out in the P FUI project 8.2.2 . We defined a SynDEx UML profile for functional specifications. We developed a gateway between the P pivot formalism and SynDEx. This gateway deals with the data-flow modeling part of the P formalism which is compliant with the Simulink subset blocks supported by the P project, except for the IF, FOR, MERGE and MUX blocks. Presently, we enhance the gateway to include these blocks and we collaborate with the other partners to define the architectural part of the P formalism. This part is intended to replace the non functional specifications, presently described with the UML profile MARTE (Modeling and Analysis of Real-Time Embedded Systems).

6.10.4. SynDEx updates with new results

We released an alpha version of SynDEx V8. This version is based on a new textual language whose compiler may be launched with command-lines featuring various options. In SynDEx V8, the adequation heuristic which performs the multiprocessor real-time schedulability analysis on multi-periodic applications, is based on the theorems and algorithms provided in the Mohamed Marouf's thesis defended last year in the team. These algorithms have been deeply improved for better consideration of data dependencies in the case of multiprocessor architectures. On the other hand, the new heuristic generates a scheduling table composed of, in addition to the usual permanent phase, a transient phase that takes into account the distribution constraints defined by the user in the multi-periodic applications as well as in the mono-periodic applications.

6.11. Probabilistic Real-Time Systems

Participants: Liliana Cucu-Grosjean, Adriana Gogonel, Codé Lo, Dorin Maxim, Cristian Maxim.

The advent of complex hardware, in response to the increasing demand for computing power in next generation systems, exacerbates some of the limitations of static timing analysis for the estimation of the worst-case execution time (WCET) estimation. In particular, the effort of acquiring (1) detail information on the hardware to develop an accurate model of its execution latency as well as (2) knowledge of the timing behaviour of the program in the presence of varying hardware conditions, such as those dependent on the history of previously executed instructions. These problems are also known as the timing analysis walls. The probabilistic timing analysis, a novel approach to the analysis of the timing behaviour of next-generation real-time embedded systems, provides answers to timing analysis walls. In [17], [48], [31] timing analysis attacks the timing analysis walls. We have also presented experimental evidence that shows how probabilistic timing analysis reduces the extent of knowledge about the execution platform required to produce probabilistically-safe and tight WCET estimations.

Based on existing estimations of WCET or minimal inter-arrival time, one may propose different probabilistic schedulability analyses [39]. These results were reported in the (PhD thesis of Dorin Maxim, mostly conducted in the Inria TRIO team (before its completion and the move to Aoste in Sept 2013).

2013 was also the year when through several invited talks [26], [28], [27], we had the opportunity to underline historical misunderstandings on probabilistic real-time systems. The most common is related to the notion of independence that is used with a wrong meaning by different papers.

GEOMETRICA Project-Team

6. New Results

6.1. Mesh Generation and Geometry Processing

6.1.1. *Splat-based Surface Reconstruction from Defect-Laden Point Sets.*

Participant: Mariette Yvinec.

In collaboration with Pierre Alliez (EPI Titane), Ricard Campos (University of Girona), Raphael Garcia (University of Girona)

We introduce a method for surface reconstruction from point sets that is able to cope with noise and outliers. First, a splat-based representation is computed from the point set. A robust local 3D RANSAC-based procedure is used to filter the point set for outliers, then a local jet surface – a low-degree surface approximation – is fitted to the inliers. Second, we extract the reconstructed surface in the form of a surface triangle mesh through Delaunay refinement. The Delaunay refinement meshing approach requires computing intersections between line segment queries and the surface to be meshed. In the present case, intersection queries are solved from the set of splats through a 1D RANSAC procedure. [14].

6.1.2. *Constructing Intrinsic Delaunay Triangulations of Submanifolds*

Participants: Jean-Daniel Boissonnat, Ramsay Dyer.

In collaboration with Arijit Ghosh (Indian Statistical Institute)

We describe an algorithm to construct an intrinsic Delaunay triangulation of a smooth closed submanifold of Euclidean space [42]. Using results established in a companion paper on the stability of Delaunay triangulations on δ -generic point sets, we establish sampling criteria which ensure that the intrinsic Delaunay complex coincides with the restricted Delaunay complex and also with the recently introduced tangential Delaunay complex. The algorithm generates a point set that meets the required criteria while the tangential complex is being constructed. In this way the computation of geodesic distances is avoided, the runtime is only linearly dependent on the ambient dimension, and the Delaunay complexes are guaranteed to be triangulations of the manifold.

6.1.3. *Delaunay Triangulation of Manifolds*

Participants: Jean-Daniel Boissonnat, Ramsay Dyer.

In collaboration with Arijit Ghosh (Indian Statistical Institute)

We present an algorithmic framework for producing Delaunay triangulations of manifolds [44]. The input to the algorithm is a set of sample points together with coordinate patches indexed by those points. The transition functions between nearby coordinate patches are required to be bi-Lipschitz with a constant close to 1. The primary novelty of the framework is that it can accommodate abstract manifolds that are not presented as submanifolds of Euclidean space. The output is a manifold simplicial complex that is the Delaunay complex of a perturbed set of points on the manifold. The guarantee of a manifold output complex demands no smoothness requirement on the transition functions, beyond the bi-Lipschitz constraint. In the smooth setting, when the transition functions are defined by common coordinate charts, such as the exponential map on a Riemannian manifold, the output manifold is homeomorphic to the original manifold, when the sampling is sufficiently dense.

6.1.4. *Anisotropic Delaunay Meshes of Surfaces*

Participants: Jean-Daniel Boissonnat, Mariette Yvinec.

In collaboration with Jane Tournois (GeometryFactory) and Kan-Le Shi (Tsing Hua University)

Anisotropic simplicial meshes are triangulations with elements elongated along prescribed directions. Anisotropic meshes have been shown to be well suited for interpolation of functions or solving PDEs. They can also significantly enhance the accuracy of a surface representation. Given a surface S endowed with a metric tensor field, we propose a new approach to generate an anisotropic mesh that approximates S with elements shaped according to the metric field [13], [47]. The algorithm relies on the well-established concepts of restricted Delaunay triangulation and Delaunay refinement and comes with theoretical guarantees. The star of each vertex in the output mesh is Delaunay for the metric attached to this vertex. Each facet has a good aspect ratio with respect to the metric specified at any of its vertices. The algorithm is easy to implement. It can mesh various types of surfaces like implicit surfaces, polyhedra or isosurfaces in 3D images. It can handle complicated geometries and topologies, and very anisotropic metric fields.

6.2. Topological and Geometric Inference

6.2.1. An Efficient Data Structure for Computing Persistent Cohomology

Participants: Jean-Daniel Boissonnat, Clément Maria.

In collaboration with Tamal Dey (Ohio State University)

Persistent homology with coefficients in a field F coincides with the same for cohomology because of duality. We propose an implementation of a recently introduced algorithm for persistent cohomology that attaches annotation vectors with the simplices. We separate the representation of the simplicial complex from the representation of the cohomology groups, and introduce a new data structure for maintaining the annotation matrix, which is more compact and reduces substantially the amount of matrix operations. In addition, we propose a heuristic to further simplify the representation of the cohomology groups and improve both time and space complexities. The paper provides a theoretical analysis, as well as a detailed experimental study of our implementation and comparison with state-of-the-art software for persistent homology and cohomology [41], [29].

6.2.2. Multi-Field Persistent Homology

Participants: Jean-Daniel Boissonnat, Clément Maria.

In [46], we introduce the *multi-field persistence diagram* for the persistence homology of a filtered complex. It encodes compactly the *superimposition* of the persistence diagrams of the complex with several field coefficients, and provides a substantially more precise description of the topology of the filtered complex. Specifically, the multi-field persistence diagram encodes the Betti numbers of integral homology and the prime divisors of the torsion coefficients of the underlying shape. Moreover, it enjoys similar stability properties as the ones of standard persistence diagrams, with the appropriate notion of distance. These properties make the multi-field persistence diagram a useful tool in computational topology. The multi-field algorithms are, in practice, as fast as algorithms that compute persistent homology in a single field.

6.2.3. Zigzag Zoology: Rips Zigzags for Homology Inference

Participants: Steve Oudot, Donald Sheehy.

For points sampled near a compact set X , the persistence barcode of the Rips filtration built from the sample contains information about the homology of X as long as X satisfies some geometric assumptions. The Rips filtration is prohibitively large, however zigzag persistence can be used to keep the size linear. We present several species of Rips-like zigzags and compare them with respect to the signal-to-noise ratio, a measure of how well the underlying homology is represented in the persistence barcode relative to the noise in the barcode at the relevant scales. Some of these Rips-like zigzags have been available as part of the Dionysus library for several years while others are new. Interestingly, we show that some species of Rips zigzags will exhibit less noise than the (non-zigzag) Rips filtration itself. Thus, Rips zigzags can offer improvements in both size complexity and signal-to-noise ratio. Along the way, we develop new techniques for manipulating and comparing persistence barcodes from zigzag modules. In particular, we give methods for reversing arrows and removing spaces from a zigzag while controlling the changes occurring in its barcode. We also discuss

factoring zigzags and a kind of interleaving of two zigzags that allows their barcodes to be compared. These techniques were developed to provide our theoretical analysis of the signal-to-noise ratio of Rips-like zigzags, but they are of independent interest as they apply to zigzag modules generally [33].

6.2.4. Efficient and Robust Topological Data Analysis on Metric Spaces

Participants: Mickaël Buchet, Frédéric Chazal, Steve Oudot, Donald Sheehy.

We extend the notion of the distance to a measure from Euclidean space to probability measures on general metric spaces as a way to perform topological data analysis in a way that is robust to noise and outliers. We then give an efficient way to approximate the sub-level sets of this function by a union of metric balls and extend previous results on sparse Rips filtrations to this setting. This robust and efficient approach to topological data analysis is illustrated with several examples from an implementation [54].

6.2.5. Noise-Adaptive Shape Reconstruction from Raw Point Sets

Participant: David Cohen-Steiner.

In collaboration with Pierre Alliez (EPI Titane), Simon Giraudot (EPI Titane)

We propose a noise-adaptive shape reconstruction method specialized to smooth, closed hypersurfaces. Our algorithm takes as input a defect-laden point set with variable noise and outliers, and comprises three main steps. First, we compute a novel type of robust distance function to the data. As a robust distance function, its sublevel-sets have the correct homotopy type when the data is a sufficiently good sample of a regular shape. The new feature is a built-in scale selection mechanism that adapts to the local noise level, under the assumption that the inferred shape is a smooth submanifold of known dimension. Second, we estimate the sign and confidence of the function at a set of seed points, based on estimated crossing parities along the edges of a uniform random graph. That component is inspired by the classical MAXCUT relaxation, except that we only require a linear solve as opposed to an eigenvector computation. Third, we compute a signed implicit function through a random walker approach with soft constraints chosen as the most confident seed points computed in previous step. The resulting pipeline is scalable and offers excellent behavior for data exhibiting variable noise levels [19].

6.2.6. Optimal Rates of Convergence for Persistence Diagrams in Topological Data Analysis

Participants: Frédéric Chazal, Marc Glisse, Bertrand Michel.

In collaboration with Catherine Labruère (Université de Bourgogne).

Computational topology has recently known an important development toward data analysis, giving birth to the field of topological data analysis. Topological persistence, or persistent homology, appears as a fundamental tool in this field. In this paper [57] (to appear in proc. ICML 2014), we study topological persistence in general metric spaces, with a statistical approach. We show that the use of persistent homology can be naturally considered in general statistical frameworks and persistence diagrams can be used as statistics with interesting convergence properties. Some numerical experiments are performed in various contexts to illustrate our results.

6.2.7. Bootstrap and Stochastic Convergence for Persistence Diagrams and Landscapes

Participant: Frédéric Chazal.

In collaboration with B. Fasy (Tulane University), F. Lecci, A. Rinaldo, A. Singh, L. Wasserman (Carnegie Mellon University).

Persistent homology probes topological properties from point clouds and functions. By looking at multiple scales simultaneously, one can record the births and deaths of topological features as the scale varies. We can summarize the persistent homology with the persistence landscape, introduced by Bubenik, which converts a diagram into a well-behaved real-valued function. We investigate the statistical properties of landscapes, such as weak convergence of the average landscapes and convergence of the bootstrap. In addition, we introduce an alternate functional summary of persistent homology, which we call the silhouette, and derive an analogous statistical theory [55].

6.2.8. *Gromov-Hausdorff Approximation of Metric Spaces with Linear Structure*

Participant: Frédéric Chazal.

In collaboration with S. Jian (Tsinghua University).

In many real-world applications data come as discrete metric spaces sampled around 1-dimensional filamentary structures that can be seen as metric graphs. In this paper [58] we address the metric reconstruction problem of such filamentary structures from data sampled around them. We prove that they can be approximated, with respect to the Gromov-Hausdorff distance by well-chosen Reeb graphs (and some of their variants) and we provide an efficient and easy to implement algorithm to compute such approximations in almost linear time. We illustrate the performances of our algorithm on a few synthetic and real data sets.

6.2.9. *Analysis and Visualization of Maps Between Shapes*

Participants: Frédéric Chazal, Maks Ovsjanikov.

In collaboration with L. Guibas (Stanford University), M. Ben Chen (Technion).

In this work we propose a method for analyzing and visualizing individual maps between shapes, or collections of such maps [23]. Our method is based on isolating and highlighting areas where the maps induce significant distortion of a given measure in a multi-scale way. Unlike the majority of prior work which focuses on discovering maps in the context of shape matching, our main focus is on evaluating, analyzing and visualizing a given map, and the distortion(s) it introduces, in an efficient and intuitive way. We are motivated primarily by the fact that most existing metrics for map evaluation are quadratic and expensive to compute in practice, and that current map visualization techniques are suitable primarily for global map understanding, and typically do not highlight areas where the map fails to meet certain quality criteria in a multi-scale way. We propose to address these challenges in a unified way by considering the functional representation of a map, and performing spectral analysis on this representation. In particular, we propose a simple multi-scale method for map evaluation and visualization, which provides detailed multi-scale information about the distortion induced by a map, which can be used alongside existing global visualization techniques.

6.2.10. *Map-Based Exploration of Intrinsic Shape Differences and Variability*

Participants: Frédéric Chazal, Maks Ovsjanikov.

In collaboration with L. Guibas and Raif Rustamov (Stanford University), M. Ben Chen and O. Azencot (Technion).

We develop a novel formulation for the notion of shape differences, aimed at providing detailed information about the location and nature of the differences or distortions between the two shapes being compared [27]. Our difference operator, derived from a shape map, is much more informative than just a scalar global shape similarity score, rendering it useful in a variety of applications where more refined shape comparisons are necessary. The approach is intrinsic and is based on a linear algebraic framework, allowing the use of many common linear algebra tools (e.g. SVD, PCA) for studying a matrix representation of the operator. Remarkably, the formulation allows us not only to localize shape differences on the shapes involved, but also to compare shape differences across pairs of shapes, and to analyze the variability in entire shape collections based on the differences between the shapes. Moreover, while we use a map or correspondence to define each shape difference, consistent correspondences between the shapes are not necessary for comparing shape differences, although they can be exploited if available. We give a number of applications of shape differences, including parameterizing the intrinsic variability in a shape collection, exploring shape collections using local variability at different scales, performing shape analogies, and aligning shape collections.

6.2.11. *An operator Approach to Tangent Vector Field Processing*

Participants: Frédéric Chazal, Maks Ovsjanikov.

In collaboration with M. Ben Chen and O. Azencot (Technion).

In this work [34], we introduce a novel coordinate-free method for manipulating and analyzing vector fields on discrete surfaces. Unlike the commonly used representations of a vector field as an assignment of vectors to the faces of the mesh, or as real values on edges, we argue that vector fields can also be naturally viewed as operators whose domain and range are functions defined on the mesh. Although this point of view is common in differential geometry it has so far not been adopted in geometry processing applications. We recall the theoretical properties of vector fields represented as operators, and show that composition of vector fields with other functional operators is natural in this setup. This leads to the characterization of vector field properties through commutativity with other operators such as the Laplace-Beltrami and symmetry operators, as well as to a straight-forward definition of differential properties such as the Lie derivative. Finally, we demonstrate a range of applications, such as Killing vector field design, symmetric vector field estimation and joint design on multiple surfaces.

6.3. Data Structures and Robust Geometric Computation

6.3.1. *The Stability of Delaunay triangulations*

Participants: Jean-Daniel Boissonnat, Ramsay Dyer.

In collaboration with Arijit Ghosh (Indian Statistical Institute)

We introduce a parametrized notion of genericity for Delaunay triangulations which, in particular, implies that the Delaunay simplices of δ -generic point sets are thick [45]. Equipped with this notion, we study the stability of Delaunay triangulations under perturbations of the metric and of the vertex positions. We quantify the magnitude of the perturbations under which the Delaunay triangulation remains unchanged.

6.3.2. *Delaunay Stability via Perturbations*

Participants: Jean-Daniel Boissonnat, Ramsay Dyer.

In collaboration with Arijit Ghosh (Indian Statistical Institute)

We present an algorithm that takes as input a finite point set in Euclidean space, and performs a perturbation that guarantees that the Delaunay triangulation of the resulting perturbed point set has quantifiable stability with respect to the metric and the point positions [43]. There is also a guarantee on the quality of the simplices: they cannot be too flat. The algorithm provides an alternative tool to the weighting or refinement methods to remove poorly shaped simplices in Delaunay triangulations of arbitrary dimension, but in addition it provides a guarantee of stability for the resulting triangulation.

6.3.3. *Deletions in 3D Delaunay Triangulation*

Participant: Olivier Devillers.

In collaboration with Kevin Buchin (Technical University Eindhoven, The Netherlands), Wolfgang Mulzer (Freie Universität Berlin, Germany), Okke Schrijvers, (Stanford University, USA) and Jonathan Shewchuk (University of California at Berkeley, USA)

Deleting a vertex in a Delaunay triangulation is much more difficult than inserting a new vertex because the information present in the triangulation before the deletion is difficult to exploit to speed up the computation of the new triangulation.

The removal of the tetrahedra incident to the deleted vertex creates a hole in the triangulation that need to be retriangulated. First we propose a technically sound framework to compute incrementally a triangulation of the hole vertices: *the conflict Delaunay triangulation*. The conflict Delaunay triangulation matches the hole boundary and avoid to compute extra tetrahedra outside the hole. Second, we propose a method that uses *guided randomized reinsertion* to speed up the point location during the computation of the conflict triangulation. The hole boundary is a polyhedron, this polyhedron is simplified by deleting its vertices one by one in a random order maintaining a polyhedron called *link Delaunay triangulation*, then the points are inserted in reverse order into the conflict Delaunay triangulation using the information from the link Delaunay triangulation to avoid point location [30].

6.3.4. *A Convex Body with a Chaotic Random Polytope*

Participants: Olivier Devillers, Marc Glisse, Rémy Thomasse.

Consider a sequence of points in a convex body in dimension d whose convex hull is dynamically maintained when the points are inserted one by one, the convex hull size may increase, decrease, or being constant when a new point is added. Studying the expected size of the convex hull when the points are evenly distributed in the convex is a classical problem of probabilistic geometry that yields to some surprising facts. For example, although it seems quite natural to think that the expected size of the convex hull is increasing with n the number of points, this fact is only formally proven for n big enough [16]. The asymptotic behavior of the expected size is known to be logarithmic for a polyhedral body and polynomial for a smooth one. If for a polyhedral or a smooth body, the asymptotic behavior is *somehow* “nice” it is possible to construct strange convex objects that have no such nice behaviors and we exhibit a convex body, such that the behavior of the expected size of a random polytope oscillates between the polyhedral and smooth behaviors when n increases [51].

6.3.5. *Delaunay Triangulations and Cycles on Closed Hyperbolic surfaces*

Participants: Mikhail Bogdanov, Monique Teillaud.

This work [40] is motivated by applications of *periodic* Delaunay triangulations in the Poincaré disk conformal model of the hyperbolic plane \mathbb{H}^2 . A periodic triangulation is defined by an infinite point set that is the image of a finite point set by a (non commutative) discrete group G generated by hyperbolic translations, such that the hyperbolic area of a Dirichlet region is finite (i.e., a cocompact Fuchsian group acting on \mathbb{H}^2 without fixed points).

We consider the projection of such a Delaunay triangulation onto the closed orientable hyperbolic surface $M = \mathbb{H}^2/G$. The graph of its edges may have cycles of length one or two. We prove that there always exists a finite-sheeted covering space of M in which there is no cycle of length ≤ 2 . We then focus on the group defining the Bolza surface (homeomorphic to a torus having two handles), and we explicitly construct a sequence of subgroups of finite index allowing us to exhibit a covering space of the Bolza surface in which, for any input point set, there is no cycle of length one, and another covering space in which there is no cycle of length two. We also exhibit a small point set such that the projection of the Delaunay triangulation on the Bolza surface for any superset has no cycle of length ≤ 2 .

The work uses mathematical proofs, algorithmic constructions, and implementation.

6.3.6. *Universal Point Sets for Planar Graph Drawings with Circular Arcs*

Participant: Monique Teillaud.

In collaboration with Patrizio Angelini (Roma Tre University), David Eppstein (University of California, Irvine), Fabrizio Frati (The University of Sydney), Michael Kaufmann (MPI, Tübingen), Sylvain Lazard (EPI VEGAS), Tamara Mchedlidze (Karlsruhe Institute of Technology), and Alexander Wolff (Universität Würzburg).

We prove that there exists a set S of n points in the plane such that every n -vertex planar graph G admits a plane drawing in which every vertex of G is placed on a distinct point of S and every edge of G is drawn as a circular arc. [25]

6.3.7. *A Generic Implementation of dD Combinatorial Maps in CGAL*

Participant: Monique Teillaud.

In collaboration with Guillaume Damiand (Université de Lyon, LIRIS, UMR 5205 CNRS)

We present a generic implementation of dD combinatorial maps and linear cell complexes in CGAL. A combinatorial map describes an object subdivided into cells; a linear cell complex describes the linear geometry embedding of such a subdivision. In this paper [49], we show how generic programming and new techniques recently introduced in the C++11 standard allow a fully generic and customizable implementation of these two data structures, while maintaining optimal memory footprint and direct access to all information. To the best of our knowledge, the CGAL software packages presented here [59], [60] offer the only available generic implementation of combinatorial maps in any dimension.

6.3.8. *Silhouette of a Random Polytope*

Participant: Marc Glisse.

In collaboration with Sylvain Lazard and Marc Pouget (EPI VEGAS) and Julien Michel (LMA-Poitiers).

We consider random polytopes defined as the convex hull of a Poisson point process on a sphere in \mathbb{R}^3 such that its average number of points is n . We show [52] that the expectation over all such random polytopes of the maximum size of their silhouettes viewed from infinity is $\Theta(\sqrt{n})$.

6.3.9. *A New Approach to Output-Sensitive Voronoi Diagrams and Delaunay Triangulations*

Participant: Donald Sheehy.

In collaboration with Gary Miller (Carnegie Mellon University)

We describe [35] a new algorithm for computing the Voronoi diagram of a set of n points in constant-dimensional Euclidean space. The running time of our algorithm is $O(f \log n \log \Delta)$ where f is the output complexity of the Voronoi diagram and Δ is the spread of the input, the ratio of largest to smallest pairwise distances. Despite the simplicity of the algorithm and its analysis, it improves on the state of the art for all inputs with polynomial spread and near-linear output size. The key idea is to first build the Voronoi diagram of a superset of the input points using ideas from Voronoi refinement mesh generation. Then, the extra points are removed in a straightforward way that allows the total work to be bounded in terms of the output complexity, yielding the output sensitive bound. The removal only involves local flips and is inspired by kinetic data structures.

6.3.10. *A Fast Algorithm for Well-Spaced Points and Approximate Delaunay Graphs*

Participant: Donald Sheehy.

In collaboration with Gary Miller and Ameya Velingker (Carnegie Mellon University)

We present [32] a new algorithm that produces a well-spaced superset of points conforming to a given input set in any dimension with guaranteed optimal output size. We also provide an approximate Delaunay graph on the output points. Our algorithm runs in expected time $O(2^{O(d)}(n \log n + m))$, where n is the input size, m is the output point set size, and d is the ambient dimension. The constants only depend on the desired element quality bounds.

To gain this new efficiency, the algorithm approximately maintains the Voronoi diagram of the current set of points by storing a superset of the Delaunay neighbors of each point. By retaining quality of the Voronoi diagram and avoiding the storage of the full Voronoi diagram, a simple exponential dependence on d is obtained in the running time. Thus, if one only wants the approximate neighbors structure of a refined Delaunay mesh conforming to a set of input points, the algorithm will return a size $2^{O(d)}m$ graph in $2^{O(d)}(n \log n + m)$ expected time. If m is superlinear in n , then we can produce a hierarchically well-spaced superset of size $2^{O(d)}n$ in $2^{O(d)}n \log n$ expected time.

6.3.11. *Geometric Separators and the Parabolic Lift*

Participant: Donald Sheehy.

A geometric separator for a set U of n geometric objects (usually balls) is a small (sublinear in n) subset whose removal disconnects the intersection graph of U into roughly equal sized parts. These separators provide a natural way to do divide and conquer in geometric settings. A particularly nice geometric separator algorithm originally introduced by Miller and Thurston has three steps: compute a centerpoint in a space of one dimension higher than the input, compute a conformal transformation that “centers” the centerpoint, and finally, use the computed transformation to sample a sphere in the original space. The output separator is the subset of S intersecting this sphere. It is both simple and elegant. We show [36] that a change of perspective (literally) can make this algorithm even simpler by eliminating the entire middle step. By computing the centerpoint of the points lifted onto a paraboloid rather than using the stereographic map as in the original method, one can sample the desired sphere directly, without computing the conformal transformation.

INDES Project-Team

6. New Results

6.1. Security

Participants: Ilaria Castellani, Bernard Serpette [correspondant], José Santos.

6.1.1. *Stateful Declassification Policies for Event-Driven Programs*

We propose a novel mechanism for enforcing information flow policies with support for declassification on event-driven programs. Declassification policies consist of two functions. First, a projection function specifies for each confidential event what information in the event can be declassified directly. Second, a stateful release function specifies the aggregate information about all confidential events seen so far that can be declassified. We provide evidence that such declassification policies are useful in the context of JavaScript web applications. An enforcement mechanism for our policies is presented and its soundness and precision are proven. Finally, we give evidence of practicality by implementing and evaluating the mechanism in a browser.

Report and mechanization can be found in <http://people.cs.kuleuven.be/~mathy.vanhoef/declass>.

6.1.2. *A Monitor Inlining Compiler for Securing JavaScript Programs*

JavaScript applications can include untrusted code dynamically loaded from third party code providers (such as online advertisements). This issue raises the need for enforcement mechanisms to ensure security properties for JavaScript programs. The dynamic nature of the JavaScript programming language makes it a hard target for static analysis. Hence, research on mechanisms for enforcing security properties for JavaScript programs has mostly focused on dynamic approaches, such as runtime monitoring and program instrumentation. We design and implement a novel compiler that inlines a security monitor and we formally prove it correct with respect to an information flow security property. To the best of our knowledge, it is the first proven correct information flow monitor inlining transformation for JavaScript programs.

Report can be found in <http://www-sop.inria.fr/indes/ifJS>. See also software section.

6.1.3. *Modular Extensions of Security Monitors for Web APIs: The DOM API Case Study*

JavaScript programs often interact with the web page on which they are included, as well as with the browser itself, through external APIs such as the DOM API, the XMLHttpRequest API, and the W3C Geolocation API. The continuous emergence and heterogeneity of different external APIs renders the problem of precisely reasoning about JavaScript security particularly challenging. To tackle this problem, we propose a methodology for extending arbitrary sound JavaScript monitors. The methodology allows us to prove noninterference for external APIs in a modular way. Thus, when considering new external APIs, the noninterference property of the security monitor still holds. We present two groups of DOM interfaces that illustrate how to extend a noninterferent monitor model with: (1) basic DOM methods, for which we have discovered new information leaks not explored in previous work; (2) live collections, which are special features of the DOM API with an unconventional semantics that can lead to several previously unknown information leaks. Finally, we inline an extensible noninterferent JavaScript monitor that handles (1) and (2), and we make it available online

Report can be found in <http://www-sop.inria.fr/indes/ifJS>.

6.1.4. *A Certified Lightweight Non-Interference Java Bytecode Verifier*

We propose a type system to verify the non-interference property in the Java Virtual Machine. We verify the system in the Coq theorem prover.

Noninterference guarantees the absence of illicit information flow throughout program execution. It can be enforced by appropriate information flow type systems. Much of the previous work on type systems for non-interference has focused on calculi or high-level programming languages, and existing type systems for low-level languages typically omit objects, exceptions and method calls. We define an information flow type system for a sequential JVM-like language that includes all these programming features, and we prove, in the Coq proof assistant, that it guarantees non-interference. An additional benefit of the formalisation is that we have extracted from our proof a certified lightweight bytecode verifier for information flow. Our work provides, to the best of our knowledge, the first sound and certified information flow type system for such an expressive fragment of the JVM.

This work appeared in the journal of Mathematical Structures in Computer Science [9].

6.1.5. *Session types for liveness and security*

Within the COST Action BETTY, we have started studying the interplay between liveness properties and secure information flow properties in session calculi, in collaboration with a colleague from Torino University. Recent developments in static analysis techniques have shown that behavioural types, and in particular session types, may be used to enforce liveness properties of communicating systems. Examples of such properties are deadlock freedom, eventual message delivery and session termination. Because secure information flow in communicating systems depends on the observation of messages, there is a clear connection between information flow analysis and the liveness properties of the systems under consideration. We have been examining the joint application of liveness enforcement and secure information flow analysis in session calculi. It appears that, by strengthening the assumptions on the liveness of systems, it is possible to relax the conditions under which a system satisfies secure information flow properties. This is ongoing work, which is expected to continue within the BETTY Action.

6.1.6. *Noninterference in reactive synchronous languages*

We defined two properties of Reactive Noninterference (RNI) for a core synchronous reactive language called CRL formalising secure information flow. Both properties are time-insensitive and termination-insensitive. Again, coarse-grained RNI is more abstract than fine-grained RNI.

Finally, a type system guaranteeing both security properties was presented. Thanks to a design choice of CRL, which offers two separate constructs for loops and iteration, and to refined typing rules, this type system allows for a precise treatment of termination leaks, which are an issue in parallel languages.

This work has been presented at the International Symposium on Trustworthy Global Computing (TGC 2013) [11]. It is also described in Attar's PhD thesis `pejman:tel-00920152`.

6.2. Models, semantics, and languages

Participants: Pejman Attar, Gérard Berry, Gérard Boudol, Ilaria Castellani, Johan Grande, Cyprien Nicolas, Tamara Rezk, Manuel Serrano [correspondant].

6.2.1. *Formalization and Concretization of Ordered Networks*

Overlay networks have been extensively studied as a solution to the dynamic nature, scale and heterogeneity of large computing platforms, and are a fundamental layers of most existing peer-to-peer networks. The basic mechanism offered by an overlay network, is routing, i.e., the mechanism enabling the delivery of messages from any node to any other node in the network. On top of routing are built crucial functionalities of peer-to-peer networks, such as networks maintenance (nodes joining and leaving the network) and information distribution and retrieval. Over the years, different topologies and routing mechanisms have been proposed in literature. However, there is a lack of formal works unifying these different designs and establishing their correctness. This paper proposes a formal common basis, partially validated with the Coq theorem prover, with the nice property of only requiring the definition of a total order on the nodes. We investigate how such a basic design can be used to build deadlock/livelock-free algorithms for routing, node insertion, and node deletion in the fault-free environment. The genericity of our design is then explored through the construction of orders on

nodes corresponding to different topologies commonly encountered in the peer-to-peer domain. To validate the methodology proposed, a simulator tool was developed. This tool is able, given the definition of an order and the definition of shortcuts, to simulate the corresponding overlay network and to explore its performance.

6.2.2. *Absence Prediction in Esterel*

We have formally proved, with the Coq system, the correctness of an absence prediction of Esterel's signals. For this we have formalised in Coq the static analysis and the interpreter written in Scheme (see the previous activity report). With this formal specification, we prove the correctness of the analysis: if a signal is considered absent by the evaluator at one instant, then this signal will be not emitted during this instant. This work is described in a currently submitted paper.

6.2.3. *Reactive Synchronous Languages*

CRL: We have studied the security property of noninterference in a synchronous Core Reactive Language (CRL). In the synchronous reactive paradigm, programs communicate by means of broadcast events, and their parallel execution is regulated by a notion of instant.

We have first shown that CRL programs are indeed reactive, namely that they always converge to a state of termination or suspension ("end of instant") in a finite number of steps. This property is important as it also entails the reactivity of a program to its environment, namely its capacity to input events from the environment at the start of instants, and to output events to the environment at the end of instants. While classical in synchronous languages, this property required to be established afresh in CRL, since this language makes use of a new asymmetric parallel operator.

We defined two bisimulation equivalences on CRL programs, corresponding respectively to a fine-grained and to a coarse-grained observation of programs. We showed that coarse-grained bisimilarity is more abstract than fine-grained bisimilarity, as it is insensitive to the order of generation of events and to repeated emissions of the same event during an instant.

DSL_M :

We have finalised our work on the language DSL_M (Dynamic Synchronous Language with Memory), which is an extension of CRL with memory and distribution. There are now several sites, and agents may migrate between sites. Two main properties are established for DSL_M: reactivity of each agent and absence of data-races between agents. Since DSL_M uses the same asymmetric parallel operator as CRL, reactivity is proven in a similar way. Moreover, the language offers a way to benefit from multi-core and multi-processor architectures, by means of the notion of synchronized scheduler, which abstractly models a computing resource. Each site may be expanded and contracted dynamically by varying its number of synchronized schedulers. Moreover agents can be moved transparently from one scheduler to another one within the same site. In this way one can formally model the load-balancing of agents over a site. This work is part of Pejman Attar's PhD thesis, defended in December 2013.

6.2.4. *Locking Fast*

We have studied the integration of low-level locking mechanisms in programming language execution environments. We have shown that for a given low-level locking mechanism the performance of the applications may vary significantly according to decisions taken for integrating it in the runtime system. We have studied two different aspects. First, we have shown how to accelerate C IO locking by selecting at runtime the adequate implementation and by using spin locks instead of full-fledged mutexes. Second, we have presented a new schema for improving the slow path of Java-like synchronized blocks. It consists in lifting the exception handler that is installed on the stack and which is in charge of releasing a monitor up to the closest exception handler already installed on the stack. All these optimizations have been implemented in Hop, our Web programming language. We have conducted experiments that shows significant speed up (up to 30%) for applications using locks extensively.

The synchronization lifting technique could be generalized to all the exception handlers, not only the handlers of synchronized blocks. As lifting only modifies the interception of exceptions, not the way they are thrown, it is compatible with languages such as Java or JavaScript that store a description of the stack at the moment when the exception is thrown inside the exception handlers. The technique should thus be broadly applicable. Exploring this idea is left for future work.

This work is described in the paper that will be published in the proceedings of the SAC'14 conference [12].

6.2.5. *JThread*

The *jthread* library is a library for Hop offering threads and mutexes and whose main locking function implements deadlock avoidance. Our library offers structured locking (i.e., critical sections instead of explicit `lock/unlock` functions). It supports nested locking. Our library is implemented using the preexisting *pthread* library and is offered as an alternative to the latter.

Compared to usual locking functions, our primitive relies on the programmer to provide some supplementary information such as the set of mutexes that might be acquired while owning a first one. However, for this supplementary information we chose default values that limit the need for the programmer to actually write it to a minimum.

The syntax of our locking construct is as follows:

```
(synchronize* l [:prelock p]
  expr1
  expr2
  ... )
```

where l is the list of mutexes to lock and p is a list that contains (some of ¹) the mutexes that might be locked during the execution of the body of the construct.

The implementation of this function relies on the ability to lock n mutexes at once. We found an algorithm for this that is both deadlock-free and starvation-free. Our algorithm relies on a dynamic total ordering of threads; this is inspired by Lamport's bakery algorithm.

We wrote a starvation-freedom property that applies to our real-life language with dynamic thread creation and programs that run forever on purpose. To express the property we need to define the following relation over threads:

$t_1 prec t_2$ iff. *exists* m . t_1 owns m and t_2 is waiting to lock m .

Let $prec^*$ be the symmetric transitive closure of $prec$.

The property that we chose and proved for our algorithm is:

If each non-waiting thread eventually releases all the mutexes it owns **and if** for each waiting thread t the number of threads t' s.t. $t' prec^* t$ does not tend toward *infinity* over time **then** each waiting thread eventually gets the mutexes it is waiting to lock.

We have implemented our library and integrated it to Hop. We haven't released it yet. An article is in preparation.

6.3. Web programming

Participants: Gérard Berry, Yoann Couillec, Ludovic Courtès, Cyprien Nicolas, Vincent Prunet, Tamara Rezk, Marcela Rivera, Bernard Serpette, Manuel Serrano [correspondant].

¹According to a few rules that we impose

6.3.1. Colored λ -calculus

We have extended the bicolored λ -calculus to a polychromic one. With two colors, we were able to abstract the Hop language with its ‘\$’ and ‘~’ annotations. With more than two colors, we can also model embedded languages as a query based language, for example. As for the bicolored version, we have defined a static transformation aggregating expressions of the same color. We have formally proved, with the Coq system, the correctness, the confluence and the termination of the transformation. This work has been accepted for publication at the conference JFLA’14. [14].

6.3.2. Multitier Debugging

The distributed nature of Web applications makes debugging difficult. The programming languages and tools commonly used make it even more complex. Generally the server-side and the client-side are implemented in different settings and the debugging is treated as two separated tasks: on the one hand, the debugging of the server, on the other hand, the debugging of the client. Most studies and tools focus on this last aspect. They concentrate on the debugging of JavaScript in the browser. Although useful, this only addresses one half of the problem. Considering the debugging of Web applications as a whole raises the following difficulties:

- As the server-side and the client-side are generally implemented in different languages, debuggers for the Web do not capture the whole execution of the application. Programming the server and the client in the same language helps but is not sufficient to let the debugger expose a coherent view of the whole execution as this also demands a runtime environment that enforces consistent representations of data structures and execution traces.
- The JavaScript tolerant semantics tends to defer errors raising. For instance, calling a function with an insufficient number of arguments may lead to filling a data structure with the unexpected `undefined` value which, in turn, may raise a type error when accessed. The *distance* between the error and its actual cause may be arbitrarily long which can make the relation between the two difficult to establish.
- The JavaScript event loop used for the GUI splits the execution into unrelated callback procedures which get called upon event receipts. When an error occurs, the active stack trace only contains elements relative to the current callback invocation. It is oblivious of the context of the callback. Understanding the cause of the error is then not easy.

Pursuing our research on multitier programming for the Web, we have built a programming environment which eliminates most of these problems.

- When an error is raised, the full stack trace is reported. This stack trace might contain server stack frames, client stack frames, or both. We call this a *multitier stack trace*.
- When an error occurs, either on the client or on the server, its source location is reported by the debugger.
- In *debugging mode*, types, arities, and array bounds, are strictly enforced on the server and on the client. Hence, when the execution of the program deviates from the formal semantics of the language, an error is raised immediately.

A paper currently submitted presents this debugger and exposes the salient aspects of its implementation is under submission.

6.3.3. Hop and HipHop : Multitier Web Orchestration

Our aim is to help programming rich applications driven by computers, smartphones or tablets; since they interact with various external services and devices, such applications require orchestration techniques that merge classical computing, client-server concurrency, web-based interfaces, and event-based programming. To achieve this, we extend the Hop multitier web programming platform [5] by the new HipHop domain specific language (DSL), which is based on the synchronous language Esterel. HipHop orchestrates and synchronizes internal and external activities according to timers, events generated by the network, GUIs, sensors and devices, or internally computed conditions.

Like Esterel, HipHop is a concurrent language based on the perfect synchrony hypothesis: a HipHop program repeatedly reacts in conceptual zero-delay to input events by generating output events; synchronization and communication between parallel statements is also performed in conceptual zero-delay. Perfect synchrony makes concurrent programs deterministic and deadlock-free, the only non-determinism left being that of the application environment. Its implementation is cycle-based, execution consisting of repeated atomic cycles “read inputs / compute reaction / generate outputs” in coroutine with the main Hop code. Concurrency is compiled away by static or dynamic sequential scheduling of code fragments. Cyclic execution atomicity avoids interference between computation and input-output, which is the usual source of unexpected non-determinism and synchronization problems for classical event-handler based programming.

While Esterel is limited to static applications, HipHop is designed for dynamicity. Its implementation on top of Hop makes it possible to dynamically build and run orchestration programs at any time using Hop’s reflexivity facilities. It even makes it possible to modify a HipHop program between two execution cycles. It also simplifies the language by importing Hop’s data definition facilities, expressions, modular structure, and higher-order programming features. It relies on the Web asynchronous concurrency and messaging already supported by Hop.

Using HipHop for real-life applications such as multimedia applications has been presented in an invited paper of the conference ICDCIT’14 [10].

This year, we extended the HipHop language with dynamic constructions, namely `genpar&` and `dyngenpar&`. These new constructs allow HipHop applications to parallelize treatment of event’s values without knowing *a priori* the number of values carried by a given event. `genpar&` is alike a delayed parallel map execution, while `dyngenpar&` may create new parallel branches on-demand.

HipHop was also extended with listeners, alike HTML/DOM ones. The programmer can attach functions to any element of the HipHop programme that will be triggered when an instruction is started, suspended, resumed, terminated or aborted. These listeners enable us to trace a specific part of a program, easing its debugging.

6.3.4. Hop Programming Environment

In Linux-based environments, Hop is launched using the command line or using OS init scripts. This is inadequate for the Mac OS environment where graphical user interfaces are generally used to start, stop, and control applications. To fit the Mac OS users habits we have implemented a graphical front-end to Hop. It allows users to monitor and manage Hop processes. The implemented high level graphical interface is a XCode project which has been developed in objective-C for Mac OS X 10.7/10.8.

The main functionalities developed in this graphical front-end are:

- easily manage Hop processes. This GUI allows users to start, to stop and to restart the execution of Hop processes in a simplified manner. This process is executed in an independent thread in order to prevent impacts in the main program. Even though the process becomes independent, the main program can still control the execution of the Hop process by stopping or restarting it.
- Display messages in a user-friendly way. All messages as well as standard and error outputs, generated after the launch Hop server, are captured and redirected to be displayed in the main program. This allows the user to monitor the execution of the Hop process at any time. In this way, the user can search for a specific output or display pattern. All messages can be saved in external files for further analysis.
- Launch a Hop process with specific settings. It is possible to specify the port number on which the Hop server will accept connection. The verbosity and debugging level can also be specified according to the needs. At the same time the user can activate/deactivate specific options like Zeroconf and Webdav.
- Specify additional arguments to run a Hop process in a “command line like” way. In particular situations, advanced users could need to specify some options when launching the Hop server.

Additionally, a set of scripts have been developed to facilitate the generation and distribution of this work. A group of scripts allows one to compile and build the Hop GUI without needing a graphic Xcode interface. In this way, it is possible to generate an application bundle in a local machine as well as in a remote one without needing additional graphical interfaces.

The other group of scripts allows one to generate a “ready to use” dmg image containing Hop files. This dmg image can either include the graphical user interface (GUI) or not. Due to the continuous evolution of Hop based on new requirements and bugs fixed, the latter set of scripts provides a powerful tool to improve the releasing of new product versions.

This front-end has been integrated in the main Hop development tree. The MacOS pre-compiled version is publicly available on the Hop web site <http://hop.inria.fr>.

6.3.5. *Web of Data*

We are extending the Hop programming language in order to improve its data management: the amount of data it can access, the increasing number of sources of data and the heterogeneity of data it can accept. We have made an implementation of the SPARQL query language and the ORC orchestration language in Hop. We have written a configurable interpreter of the ORC language. The parallelism of the interpreter can be activated or not, for each operator of the ORC language. This specificity allows different executions of an ORC application, depending on the execution context or constraints, such as an execution on a client which disallows any parallelism. Within the X-Data project, we have participated in the development of a data intensive application in collaboration with Data Publica, the leading company of the project, and with the Inria Zenith research team. This application analyzed data sets provided by the French Insee institute to exhibit population commuting patterns. Our incentive for participating in this development was to acquire knowledge on programming data intensive applications. In the mid-term, we will rest on this expertise to create new data-aware programming languages or programming language extensions.

6.4. *Web robotics*

Participants: Ludovic Courtès, Cyprien Nicolas, Vincent Prunet [correspondant], Manuel Serrano.

6.4.1. *Cable driven robots*

The sound design of modern robotic applications demands for the configuration-time integration of various subsystems which together constitute a robot. APIs and protocols such as ROS (Robot Operating System) provide robot designers with tools to combine software and hardware components into a complete robot. In addition, more and more robots need to share information or interact with diffuse objects available in the robot neighborhood, and also with remote services, to log data (typically activity monitoring data in the case of an assistance robot), to send information messages (alarms or triggering events to some other infrastructure), to subscribe to services provided by objects or remote servers, to provide services that may help peer entities, to get new behaviors by downloading and installing applications within the robot. We develop tools and architectures to address these requirements using Hop as our main platform. We experiment software architectures involving robots, web objects, several integration models with third party components (hardware, software computation libraries for robotics, stand-alone robots), protocols, and libraries.

We pursued the joint work with Coprin Team about using Hop to coordinate a cable-driven robot. We changed the hardware on which Hop runs to a mini-PC instead of a standard laptop, plugged a wireless router, and used the wireless network from a tablet to move the robot. We also improved the robot hardware and software. The setup has been summarized in a paper [13] and presented at a national conference on robotics.

6.4.2. *Web Robotics*

Web Robotics is a two years Inria ADT project targeting the development of technical foundations (libraries and toolkits) and demos of web enabled robots. The project is led by Indes (Vincent Prunet, Manuel Serrano), software development is supported by Inria SED (Ludovic Courtès), robots are provided by Inria Coprin. A demonstrator and dissemination platform consisting of a cable robot and dedicated web services have been set up to enable people to interact with the robot through a web server (web <http://webrobotics.inria.fr:8080/hop/welcome>).



Figure 1. A screenshot of the MacOS X Hop graphical interface.



Figure 2. A web-controlled cable robot. The whole application is implemented with Hop.

The web robotics demo demonstrates:

- the programming of robot control functions within Hop
- simulation/real hardware abstraction
- hardware control (Phidget integration)
- integration of specialized robotics libraries
- multi server architecture
- management of multiple users and authenticated access to critical resources.

Hop added value is to provide:

- an unconstrained specification environment where data and services are easily shared among servers and clients;
- a seamless, plugin free, integration into standard web browsers.

Also in 2013, Indes has joined the PAL (Person Assisted Living) Inria project, to develop web enabled applications within the project.

MARELLE Project-Team

6. New Results

6.1. Bourbaki, Sets and Ordinals

Participant: José Grimm [correspondant].

In previous years, we developed a formal library describing the part of the Bourbaki books on set theory, cardinals and ordinals, [18]. Here are some additions to the library.

Since addition of ordinals is non-commutative, the sum of n ordinals x_1 to x_n depends on their ordering; the maximum number $f(n)$ is a priori bounded by $n!$, and we have shown that it satisfies a recurrence relation (R), Bourbaki asks, in an exercise, to show that $f(n) = 81f(n - 5)$ for $n \geq 20$. This is an easy consequence of an explicit formula (F) for f . That (R) implies (F) can be expressed in pure Coq (with binary integers), but we have no idea how to prove it.

We proved some facts of the theory of models: the set V_ω of hereditarily finite sets satisfies ZF (but not the axiom of infinity); the von Neumann universe satisfies ZF and AF, there is a subset of the universe satisfying ZF containing no inaccessible cardinal. We have also studied the set of formulas and show the theorem of Löwenheim-Skolem.

The main contribution this year is the study of some families of ordinals. If the family is internally closed and too big to be a set, then it is the image of a normal (continuous and strictly increasing) function, called the enumeration function of the family. The family of fix-points of a normal function satisfies this property, and the enumeration of this family is called the first derived function. There is a derivation at every order. For instance, the first derivation of $x \mapsto 1 + x$ is $x \mapsto \omega x$, and the derivation of order n is $x \mapsto \phi(n, x)$. The least x such that $x = \omega^x$ is known as ϵ_0 ; the least x such that $x = \phi(x, 0)$ is known as Γ_0 .

We have shown that the inductive type T defined by zero and a constructor of type $T \rightarrow N \rightarrow T \rightarrow T$, without the terms that are not in “normal form”, is isomorphic to the set of ordinals less than ϵ_0 ; in the case of $T \rightarrow T \rightarrow N \rightarrow T \rightarrow T$, we get all ordinals less than Γ_0 ; we have also studied the case with one more T (the first two types were first implemented by Castéran, the last was suggested by Ackermann) [19]

6.2. Homotopy Type Theory

Participants: Yves Bertot [correspondant], Florent Bréhard.

Homotopy Type Theory is a domain born out of the conjunction of type theory, which serves as foundations for proof systems like Coq or Agda, and homotopy theory, and domain of mathematics which is concerned with equivalence classes of objects modulo continuous deformation. In particular, Homotopy Type Theory concentrates on paths (continuous substrate between various objects) and paths between paths: paths between points can be understood as lines, paths between lines can be understood as surfaces.

In particular, paths can be thought as having the same properties as the notion of equality that is usually defined inductively in type theory systems and homotopy type theory goes against the trend started in the 1990s where specialists thought an axiom should be added to express that all paths between paths should be equal. On the contrary, if all paths between paths are not equal, type theory can be used to model homotopy theory and that domain of mathematics because a new area of applications for type theory-based theorem provers.

V. Voevodsky organized a special year at Institute for Advanced Study in Princeton on this topic, and Yves Bertot participated to this special year, during which many experiments were performed, extensions to proof systems were designed, and a book was produced. In particular, Yves Bertot devised an extension of the Coq system with *private types* which makes it possible to simulate a new concept known as *higher inductive types*. On top of this extension, the members of the special year produced a collection of higher inductive types, describing circles, spheres, truncations.

During his internship in the Marelle project, Florent Bréhard studied the equivalence between several presentations of higher-dimension spheres using higher inductive types.

Work on higher inductive types was pursued more precisely by Bruno Barras from Saclay. We expect that the result of this work will supersede the experiments made possible by Yves Bertot's implementation of private types, but the concept of private type may retain applications in other domains.

6.3. Isolation of polynomial roots

Participants: Yves Bertot [correspondant], Julianna Zsidó.

Together with techniques to produce square-free polynomials (polynomials whose roots are all simple), Bernstein polynomials provide a way to decide whether a polynomial has roots in a given interval. Together with a dichotomy procedure, this makes it possible to isolate all the roots of a polynomial, or to show that no root of a given polynomial occur in a given interval. At the end of 2012, Julianna Zsidó started to study this procedure: she showed the properties of the procedure to obtain square-free polynomials and she then formalized a proof for a theorem known as the *theorem of three circles* which plays a rôle in proving that dichotomy will terminate. This work has been published as an article in the *Journal of Automated Reasoning*.

We expect to wrap up all this work by producing easy-to-use tactics to prove properties of polynomial formulas and generalizing it to polynomials in several variables.

During a summer internship, Konstantinos Lentzos worked on the representation of algebraic numbers (which can always be represented as roots of polynomials in a given interval) and the question of finding polynomials for algebraic numbers obtained through simple operations (like addition, multiplication, opposite, and inversion). However, this work was made extremely difficult by the problem of finding morphisms between various fields definable on top of a polynomial ring.

6.4. Properties of the π number

Participants: Yves Bertot [correspondant], Laurence Rideau, Laurent Théry.

As a testbed for the progress of formalized libraries in the domain of calculus, we studied an algorithm to compute π (the circle ratio) using arithmetic-geometric means. This study brought us to extend the libraries with improper integrals, studies of *arcsinh*, variable change in integrals, and error propagation proofs.

We also studied a formal proof of the spigot algorithm designed by Bailey, Borwein, and Plouffe, which is used to compute far digits in the hexadecimal representation of π as a fractional number. This relies on floating point computations and error control, for which we provided a formal proof.

6.5. Formal study of cryptography

Participants: Gilles Barthe [IMDEA Software Institute], François Dupressoir [IMDEA Software Institute], Benjamin Grégoire [correspondant], César Kunz [IMDEA Software Institute], Yassine Lakhnech [Univ. Grenoble 1], Benedikt Schmid [IMDEA Software Institute], Pierre-Yves Strub [IMDEA Software Institute], Santiago Zanella Béguelin [MSR].

The goal of this work is to provide a friendly tool easily usable by cryptographers without knowledge of formal proof assistants. The idea is to use the techniques formally proved in Certycrypt and to call SMT-provers. We provide two different tools:

- EasyCrypt (see <http://www.easycrypt.info/>) is a toolset for reasoning about relational properties of probabilistic computations with adversarial code. Its main application is the construction and verification of game-based cryptographic proofs. This year, EasyCrypt has been fully reimplemented, allowing more modularity in proofs and an interactive prover has been integrated.
- ZooCrypt (see <http://www.easycrypt.info/zooencrypt/>) is an automated tool for analyzing the security of padding-based public-key encryption schemes (i.e. schemes built from trapdoor permutations and hash functions). ZooCrypt includes an experimental mechanism to generate EasyCrypt proofs of security of analyzed schemes.

This year we published papers concerning formal proofs for properties of elliptic curves, differential privacy, padding-based encryption, and probabilistic relational verification.

6.6. Approximation of Mathematical functions

Participants: Guillaume Hanrot, Érik Martin-Dorel, Micaela Mayero [Université de Paris 13], Ioana Paşca [Université de Nimes], Laurence Rideau, Laurent Théry [correspondant].

In a collaboration supported by ANR project Tamadi, we study the approximation of mathematical functions (exponential and trigonometric functions) using polynomial functions.

This year, we completed the formal verification of our library that computes Taylor Models for the usual mathematical functions of one variable within Coq. A presentation of this work has been done at SYNASC'2013.

The SLZ algorithm checks that there is no hard-to-round floating numbers for a given range in a given floating-point format. It usually consists of a very long computation returning a yes/no answer. Formally proving the implementation of the algorithm is current outside reach since it requires very sophisticated numerical libraries that are currently impossible to verify formally. We have defined a notion of certificate for these computations based on Hensel's lemma and derived an executable checker within Coq that is capable to verify such computations. A publication has been submitted.

6.7. Formal verification in Geometry

Participants: Laurent Fuchs, Laurent Théry [correspondant].

Grassmann-Cayley Algebras are a convenient algebraic way of talking about geometrical concepts. We have further improved our certified Grassmann-Cayley Algebra library to accommodate unbalanced binary trees. A publication has been accepted and will be published in 2014.

6.8. SMT automation for Ssreflect

Participants: Antoine Gropellier, Laurent Théry [correspondant].

The proof of the Feit-Thompson theorem (also known as the odd-order theorem) has been carried on with little use of automation. We have customised the existing connection between Coq and SMT solvers using Why to accommodate Ssreflect specificities. The preliminary results are encouraging.

APICS Project-Team

6. New Results

6.1. Source recovery problems

Participants: Laurent Baratchart, Kateryna Bashtova, Sylvain Chevillard, Juliette Leblond, Dmitry Ponomarev.

This section is concerned with inverse problems for 3-D Poisson-Laplace equations. Though the geometrical settings differ in the 2 sections below, the characterization of silent sources (that give rise to a vanishing potential at measurement points) is one of the common problems to both which has been recently achieved in the magnetization setup, see [14].

6.1.1. Application to EEG

This work is conducted in collaboration with Maureen Clerc and Théo Papadopoulo from the Athena Project-Team, and with Jean-Paul Marmorat (Centre de mathématiques appliquées - CMA, École des Mines de Paris).

In 3-D, functional or clinical active regions in the cortex are often modeled by point-wise sources that have to be localized from measurements on the scalp of a potential satisfying a Laplace equation (EEG, electroencephalography). In the work [3] it was shown how to proceed via best rational approximation on a sequence of 2-D disks cut along the inner sphere, for the case where there are at most 2 sources. Last year, a milestone was reached in the research on the behavior of poles in best rational approximants of fixed degree to functions with branch points [6], to the effect that the technique carries over to finitely many sources (see Section 4.2).

In this connection, a dedicated software “FindSources3D” is being developed, in collaboration with the team Athena and the CMA. We took on this year algorithmic developments, prompted by recent and promising contacts with the firm BESA (see Section 5.6), namely automatic detection of the number of sources (which is left to the user at the moment) and simultaneous processing of data from several time instants. It appears that in the rational approximation step, *multiple* poles possess a nice behavior with respect to branched singularities. This is due to the very physical assumptions on the model (for EEG data, one should consider *triple* poles). Though numerically observed in [8], there is no mathematical justification so far why multiple poles generate such strong accumulation of the poles of the approximants. This intriguing property, however, is definitely helping source recovery. It is used in order to automatically estimate the “most plausible” number of sources (numerically: up to 2, at the moment).

In connection with the work [14] related to inverse magnetization issues (see Section 6.1.2), the characterization of silent sources for EEG has been carried out [42]. These are sums of (distributional) derivatives of Sobolev functions vanishing on the boundary.

In a near future, magnetic data from MEG (magneto-encephalography) will become available along with EEG data; indeed, it is now possible to use simultaneously corresponding measurement devices, in order to measure both electrical and magnetic fields. This should enhance the accuracy of our source recovery algorithms.

Let us mention that discretization issues in geophysics can also be approached by such techniques. Namely, in geodesy or for GPS computations, one is led to seek a discrete approximation of the gravitational potential on the Earth’s surface, from partial data collected there. This is the topic of a beginning collaboration with physicist colleagues (IGN, LAREG, geodesy). Related geometrical issues (finding out the geoid, level surface of the gravitational potential) are worthy of consideration as well.

6.1.2. Magnetization issues

This work is carried out in the framework of the “équipe associée Inria” IMPINGE, comprising Eduardo Andrade Lima and Benjamin Weiss from the Earth Sciences department at MIT (Boston, USA) and Douglas Hardin and Edward Saff from the Mathematics department at Vanderbilt University (Nashville, USA),

Localizing magnetic sources from measurements of the magnetic field away from the support of the magnetization is the fundamental issue under investigation by IMPINGE. The goal is to determine magnetic properties of rock samples (*e.g.* meteorites or stalactites) from fine field measurements close to the sample that can nowadays be obtained using SQUIDS (supraconducting coil devices). Currently, rock samples are cut into thin slabs and the magnetization distribution is considered to lie in a plane, which makes for a somewhat less indeterminate framework than EEG as regards inverse problems because “less” magnetizations can produce the same field (for the slab has no inner volume).

The magnetization operator is the Riesz potential of the divergence of the magnetization, see (1). Last year, the problem of recovering a thin plate magnetization distribution from measurements of the field in a plane above the sample led us to an analysis of the kernel of this operator, which we characterized in various functional and distributional spaces [14]. Using a generalization of the Hodge decomposition, we were able to describe all magnetizations equivalent to a given one. Here, equivalent means that the magnetizations generate the same field from above and from below if, say, the slab is horizontal. When magnetizations have bounded support, which is the case for rock samples, we proved that magnetizations equivalent from above are also equivalent from below, but this is no longer true for unbounded supports. In fact, even for unidirectional magnetizations, uniqueness of a magnetization generating a given field depends on the boundedness of the support, as we proved that *any* magnetization is equivalent from above to a unidirectional one (with infinite support in general). This helps explaining why methods in the Fourier domain (which essentially lose track of the support information) do encounter problems. It also shows that information on the support must be used in a crucial way to solve the problem.

This year, we produced a fast inversion scheme for magnetic field maps of unidirectional planar geological magnetization with discrete support located on a regular grid, based on discrete Fourier transform [18]. Figures 5, 6, 7 and 8 show an example of reconstruction. As the just mentioned article shows, the Fourier approach is computationally attractive but undergoes aliasing phenomena that tend to offset its efficiency. In particular, estimating the total moment of the magnetization sample seems to require data extrapolation techniques which are to take place in the space domain. This is why we have started to study regularization schemes based on truncation of the support in connection with singular values analysis of the discretized problem.



Figure 5. Inria’s logo were printed on a piece of paper. The ink of the letters “In” were magnetized along a direction D_1 . The ink of the letters “ria” were magnetized along another direction D_2 (almost orthogonal to D_1).

In a joint effort by all members of IMPINGE, we set up a heuristics to recover dipolar magnetizations, using a discrete least square criterion. At the moment, it is solved by a singular value decomposition procedure of the magnetization-to-field operator, along with a regularization technique based on truncation of the support. Preliminary experiments on synthetic data give quite accurate results to recover the net moment of a sample, see the preliminary document <http://www-sop.inria.fr/apics/IMPINGE/Documents/NotesSyntheticExample.pdf>. We also ran the procedure on real data (measurements of the field generated by Lunar spherules) for which the net moment can be estimated by other methods. The net moment thus recovered matches well the expected moment.

This shows that the technique we use to reduce the support, which is based on thresholding contributions of dipoles to the observations, is capable of eliminating some nearly silent dipole distributions which flaw the

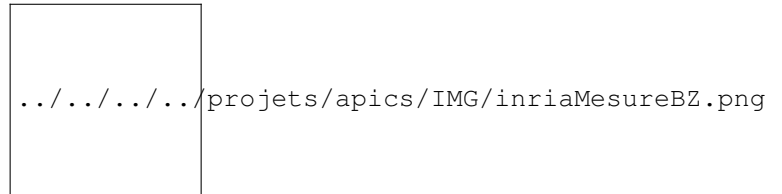


Figure 6. The Z-component of the magnetic field generated by the sample is measured by a SQUID microscope. The measure is performed $200\mu\text{m}$ above the sample.

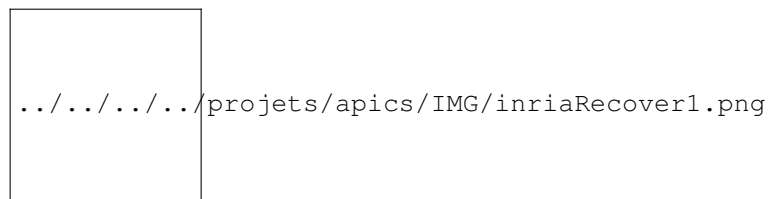


Figure 7. The field measured in Figure 6 is inverted, assuming that the sample is uni-dimensionally magnetized along the direction D_1 . The letters “In” are fairly well recovered while the rest of the letters is blurred (because the hypothesis about the direction of magnetization is false for “ria”).



Figure 8. The field measured in Figure 6 is inverted, assuming that the sample is uni-dimensionally magnetized along the direction D_2 . The letters “ria” are fairly well recovered while the rest of the letters is blurred (because the hypothesis about the direction of magnetization is false for “In”).

singular value analysis. In order to better understand the geometric nature of such distributions, and thus affirm theoretical bases to the above mentioned heuristics, we raised the question of determining an eigenbasis for the positive self adjoint operator mapping a L^2 magnetization on a rectangle to the field it generates on a rectangle parallel to the initial one. Once ordered according to decreasing eigenvalues, such a basis should retain “as much information as possible” granted the order of truncation.

This is not such an easy problem and currently, in the framework of the PhD thesis of D. Ponomarev, we investigate a simplified two-dimensional analog, defined via convolution of a function on a segment with the Poisson kernel of the upper half-plane and then restriction to a parallel segment in that half-plane. Surprisingly perhaps, this issue was apparently not considered in spite of its natural character and the fact that it makes contact with classical spectral theory. Specifically, it amounts to spectral representation of certain compressed Toeplitz operators with exponential-of-modulus symbols. Beyond the bibliographical research needed to understand the status of this question, only preliminary results have been attained so far.

6.2. Boundary value problems

Participants: Laurent Baratchart, Slah Chaabi, Sylvain Chevillard, Juliette Leblond, Dmitry Ponomarev, Elodie Pozzi.

This work was the occasion of collaborations with Alexander Borichev (Aix-Marseille University), Jonathan Partington (Univ. Leeds, UK), and Emmanuel Russ (Univ. Grenoble, IJF).

6.2.1. Generalized Hardy classes

As we mentioned in Section 4.4 2-D diffusion equations of the form $\operatorname{div}(\sigma \nabla u) = 0$ with real non-negative valued conductivity σ can be viewed as compatibility relations for the so-called conjugate Beltrami equation: $\bar{\partial} f = \nu \partial \bar{f}$ with $\nu = (1 - \sigma)/(1 + \sigma)$ [4]. Thus, the conjugate Beltrami equation is a means to replace the initial second order diffusion equation by a first order system of two real equations, merged into a single complex one. Hardy spaces under study here are those of this conjugate Beltrami equation: they are comprised of solutions to that equation in the considered domain whose L^p means over curves tending to the boundary of the domain remain bounded. They will for example replace holomorphic Hardy spaces in Problem (P) when dealing with non-constant (isotropic) conductivity. Their traces merely lie in L^p ($1 < p < \infty$), which is suitable for identification from point-wise measurements, and turn out to be dense on strict subsets of the boundary. This allows one to state Cauchy problems as bounded extremal issues in L^p classes of generalized analytic functions, in a reminiscent manner of what was done for analytic functions as discussed in Section 3.3.1 .

The study of such Hardy spaces for Lipschitz σ was reduced in [4] to that of spaces of pseudo-holomorphic functions with bounded coefficients, which were apparently first considered on the disk by S. Klimentov. Typical results here are that solution factorize as $e^s F$, where F is a holomorphic Hardy function while s is in the Sobolev space $W^{1,r}$ for all $r < \infty$ (Bers factorization), and the analog to the M. Riesz theorem which amounts to solvability of the Dirichlet problem for the initial conductivity equation with L^p boundary data for all $p \in (1, \infty)$. Over the last two years, the case of $W^{1,q}$ conductivities over finitely connected domains, $q > 2$, has been carried out in [13] [61].

In 2013, completing a study begun last year in the framework of the PhD of S. Chaabi, we established similar results in the case where $\log \sigma$ lies in $W^{1,2}$, which corresponds to the critical exponent in Vekua’s theory of pseudo-holomorphic functions. This is completely new, and apparently the first example of a solvable Dirichlet problem with L^p boundary data where the conductivity can be both unbounded and vanishing at some places. Accordingly, solutions may also be unbounded inside the domain of the equation, that is, the maximum principle no longer holds. The proof develops a refinement of the Bers factorization based on Muckenhoupt weights and on an original multiplier theorem for $\log W^{1,2}$ functions. A paper on this topic has been submitted [28].

The PhD work of S. Chaabi (defended December 2) contains further work on the Weinstein equation and certain generalizations thereof. This equation results from 2-D projection of Laplace's equation in the presence of rotation symmetry in 3-D. In particular, it is the equation governing the free boundary problem of plasma confinement in the plane section of a tokamak. A method dwelling on Fokas's approach to elliptic boundary value problems has been developed which uses Lax pairs and solves for a Riemann-Hilbert problem on a Riemann surface. It was used to devise semi-explicit forms of solutions to Dirichlet and Neumann problems for the conductivity equation satisfied by the poloidal flux.

In another connection, the conductivity equation can also be regarded as a static Schrödinger equation for smooth coefficients. In particular, a description of laser beam propagation in photopolymers can be crudely approximated by a stationary two-dimensional model of wave propagation in a medium with negligible change of refractive index. In this setting, Helmholtz equation is approximated by a linear Schrödinger equation with one spatial coordinate as evolutionary variable. This phenomenon can be described by a non-stationary model that relies on a spatial nonlinear Schrödinger (NLS) equation with time-dependent refractive index. A model problem has been considered in [20], when the rate of change of refractive index is proportional to the squared amplitude of the electric field and the spatial domain is a plane.

We have also studied composition operators on generalized Hardy spaces in the framework of [13]. In the work [32] submitted for publication, we provide necessary and/or sufficient conditions on the composition map, depending on the geometry of the domains, ensuring that these operators are bounded, invertible, isometric or compact.

6.2.2. Best constrained analytic approximation

Several questions about the behavior of solutions to the bounded extremal problem (P) of Section 3.3.1 have been considered. For instance, truncated Toeplitz operators have been studied in [17], that can be used to quantify robustness properties of our resolution schemes in H^2 and to establish error estimates. Moreover we considered additional interpolation constraints on the disk in Problem (P), and derived new stability estimates for the solution [46]. Such interpolation constraints arise naturally in inverse boundary problems like plasma shaping in last generation tokamaks, where some measurements are performed inside the chamber 4.4. Of course the version studied so far is much simplified, as it must be carried over to non-constant conductivities and annular geometries.

6.3. Synthesis of compact multiplexers and de-embedding of multiplexers

Participants: Martine Olivi, Sanda Lefteriu, Fabien Seyfert.

This work has been done in collaboration with Stéphane Bila (XLIM, Limoges, France), Hussein Ezzedin (XLIM, Limoges, France), Damien Pacaud (Thales Alenia Space, Toulouse, France), Giuseppe Macchiarella (Politecnico di Milano, Milan, Italy), and Matteo Oldoni (Siae Microelettronica, Milan, Italy).

6.3.1. Synthesis of compact multiplexers

We focused our research on multiplexer with a star topology. These are comprised of a central N -port junction, and of filters plugged on all but common ports (see Figure 9). A possible approach to synthesis of the multiplexer's response is to postulate that each filter channel has to match the multiplexer at n_k frequencies (n_k being the order of the filter) while rejecting the energy at m_k other frequencies (m_k being the order the transmission polynomial of the filter). The desired synthesis can then be cast into computing of a collection of filter's responses matching the energy as prescribed and rejecting it at specified frequencies when plugged simultaneously on the junction. Whether such a collection exists is one of the main open issues facing co-integration of systems in electronics. Investigating the latter led us to consider the simpler problem of matching a filter, on a frequency-varying load, while rejecting energy at fixed specified frequencies. If the order of the filter is n this amounts to fix a given transmission polynomial r and to solve for a unitary polynomial p meeting interpolation conditions of the form:

$$j = 1 \cdots n, \quad \frac{p}{q}(w_j) = \gamma_j, \quad |\gamma_j| < 1$$

where q is the unique monic Hurwitz polynomial satisfying the Feldtkeller equation

$$qq^* = pp^* + rr^*.$$

This problem can be seen as an extended Nevanlinna-Pick interpolation problem, which was considered in [65] when the interpolation frequencies lie in the *open* left half-plane. Last year we conjectured the existence and uniqueness of a solution, which were eventually proved true this year when r has no roots on the imaginary axis. We already communicated on the subject (9.1), and a scientific report as well as an article are being written on this result [30]. The proof relies on the local invertibility of an evaluation map that is established using a differential argument and the structure of particular Pick matrices. The case where r has zeros on the imaginary axis is of great interest, and though existence then holds again uniqueness is still not well-understood: it is conjectured that under minor restrictions on the localization of the γ'_k 's (typically off an algebraic subvariety) the main results still hold.

This research lies at heart of our collaboration with CNES on multiplexer synthesis and the core of the starting ANR project COCORAM on co-integration of filters and antennas (see Section 8.1.1).

6.3.2. De-embedding of multiplexers

Let S be the external scattering parameters of a multiplexer composed of a N -port junction with response T and $N - 1$ filters with responses F_1, \dots, F_{N-1} as plotted on Figure 9. The de-embedding problem concerns the recovery of the F_k and can be considered under different hypotheses. Last year we studied the de-embedding problem where S and T are known [76] but no particular structure on the F_k is assumed. It was shown that for a generic junction T and for $N > 3$ the de-embedding problem has a unique solution. It was however observed that in practice the junction's response is far from being generic (as it is usually obtained by assembly of smaller T -junctions) which renders the problem extremely sensitive to measurement noise. It was also noticed that in practical applications, scattering measurements of the junction are hardly available.

It was therefore natural to consider following de-embedding problem. Given S the external scattering measurement of the multiplexer, and under the assumptions:

- the F_k are rational of known McMillan degree,
- the coupling geometry of their circuital realization is known,

what can be said about the filter's responses? It was shown that under the above hypotheses, in particular with no a priori knowledge of T , the filter's responses are identifiable up to a constant chain matrix chained at their second port (nearest to the junction) [24]. It was also shown that this uncertainty bears only on the resonant frequency of the last cavity of each filter, as well as on their output coupling. Most of the filters' important parameters can therefore be recovered. The approach is constructive and relies on rational approximation of certain external scattering parameters, and on an extraction procedure similar to Darlington's synthesis for filters. Software developments have been pursued to implement the latter and practical studies are under way with data furnished by Thales Alenia Space and by Siae Microelettronica. A medium term objective is to extend the Presto-HF (5.3) software to de-embedding problems for multiplexers and more general multi-ports.

This work is pursued in collaboration with Thales Alenia Space, Siae Microelettronica, XLIM and CNES in particular under contract with CNES on compact N -port synthesis (see Section 7.1).

6.4. Detection of the instability of amplifiers

Participants: Laurent Baratchart, Sylvain Chevillard, Martine Olivi, Fabien Seyfert.

This work is conducted in collaboration with Jean-Baptiste Pomet from the McTao team. It is a continuation of a collaboration with CNES and the University of Bilbao. The goal is to help developing amplifiers, in particular to detect instability at an early stage of the design.



Figure 9. Multiplexer made of a junction T and filtering devices $F_1, F_2 \cdots F_N$

Currently, electrical engineers from the University of Bilbao, under contract with CNES (the French Space Agency), use heuristics to diagnose instability before the circuit is physically implemented. We intend to set up a rigorously founded algorithm, based on properties of transfer functions of such amplifiers which belong to particular classes of analytic functions.

In non-degenerate cases, non-linear electrical components can be replaced by their first order approximation when studying stability to small perturbations. Using this approximation, diodes appear as perfect negative resistors and transistors as perfect current sources controlled by the voltages at certain points of the circuit.

In previous years, we had proved that the class of transfer functions which can be realized with such ideal components and standard passive components (resistors, selfs, capacitors and transmission lines) is rather large since it contains all rational functions in the variable and in the exponentials thereof. This makes possible to design circuits that are unstable, although they have no pole in the right half-plane. This remains true even if a high resistor is put in parallel of the circuit, which is rather unusual. These pathological examples are unrealistic, though, because they assume that non-linear elements continue to provide gain even at very high frequencies. In practice, small capacitive and inductive effects (negligible at moderate frequencies) make these components passive for very high frequencies.

In 2013, we showed that under this simple assumption that there are small inductive and capacitive effects in active components, the class of transfer functions of realistic circuits is much smaller than in previous situation. Our main result is that a realistic circuit is unstable if and only if it has poles in the right half-plane. Moreover, there can only be finitely many of them. Besides this result, we also generalized our description of the class of transfer functions achievable with ideal components, to include the case of transmission lines with loss. An article is currently being written on this subject.

6.5. Rational and meromorphic approximation

Participants: Laurent Baratchart, Sylvain Chevillard.

This work has been done in collaboration with Herbert Stahl (Beuth-Hochsch.), Maxim Yattselev (Purdue Univ. at Indianapolis, USA), Tao Qian (Univ. Macao).

We published last year an important result in approximation theory, namely the counting measure of poles of best H^2 approximants of degree n to a function analytically continuable, except over finitely many branchpoints lying outside the unit disk, converges to the Green equilibrium distribution of the compact set of minimal Green capacity outside of which the function is single valued [6] (see also [21]). This result warrants source recovery techniques used in Section 6.1.1. We considered this year a similar problem for best uniform meromorphic approximants on the unit circle (so-called AAK approximants after Adamjan, Arov and Krein), in the case where the function may have poles and essential singularities. The technical difficulties are considerable, and though a line of attack has been adopted we presently struggle with the proof.

We also studied partial realizations, or equivalently Padé approximants to transfer functions with branchpoints. Identification techniques based on partial realizations of a stable infinite-dimensional transfer function are known to often provide unstable models, but the question as to whether this is due to noise or to intrinsic instability was not clear. This year, we published a paper showing that, in the case of 4 branchpoints, the pole behavior generically has deterministic chaos to it [15].

We also considered the issue of lower bounds in rational approximation. Prompted by renewed interest for linearizing techniques such as vector fitting in the identification community, we studied linearized errors in light of the topological approach in [51], to find that, when properly normalized, they give rise to lower bounds in L^2 rational approximation. Moreover, these make contact with AAK theory which furnishes more, easily computable lower bounds. This is an interesting finding, for lower bounds are usually difficult to get in approximation and though quite helpful to get an appraisal of what can be hoped for in modeling. Dwelling on this, we established for the first time lower bounds in L^2 rational approximation to some badly L^∞ approximable functions (Blaschke products) and showed equivalence, up to a constant, of best L^2 and L^∞ approximation to functions with branchpoints (such as those appearing in inverse source problems for

EEG, see Section 6.1.1). An article on this subject is currently submitted for publication in the Journal of Approximation Theory [29].

6.6. Tools for numerically guaranteed computations

Participant: Sylvain Chevillard.

The overall and long-term goal is to enhance the quality of numerical computations. The progress made during year 2013 is the following:

- Publication of a work with Marc Mezzarobba (who was with Aric project-team at that time, and who is now with LIP6) about the efficient evaluation of the Airy $\text{Ai}(x)$ function when x is moderately large [22]. The Taylor series of the Airy Ai function (as many others such as, e.g., Bessel functions or erf) is ill-conditioned when x is not small. To overcome this difficulty, we extend a method by Gawronski, Müller and Reinhard, known to solve the issue in the case of the error function erf. We rewrite $\text{Ai}(x)$ as $G(x)/F(x)$ where F and G are two functions with well-conditioned series. However, the coefficients of G turn out to obey a three-terms ill-conditioned recurrence. We evaluate this recurrence using Miller's backward algorithm with a rigorous error analysis. Function Ai is an example, but ideally the process could be automated to handle some appropriate class of functions in a future work.
- A more general endeavor is to develop a tool that helps developers of libms in their task. This is performed by the software Sollya ³, developed in collaboration with C. Lauter (Université Pierre et Marie Curie) and M. Joldeş (LAAS). In 2013, we released version version 4.0 (in May) and 4.1 (in November) of Sollya. Among other things these releases make available to the user all features of Sollya as a C library. They also introduce the possibility of computing Chebyshev models, and a generalization of Remez algorithm allowing the user to compute a L^∞ best approximation of a real-valued function on a bounded real interval by any linear combination of given functions.

³<http://sollya.gforge.inria.fr/>

MCTAO Project-Team

6. New Results

6.1. Optimal control for quantum systems: the contrast problem in NMR

These studies aim at optimizing the contrast in Nuclear Magnetic Resonance imaging using advanced optimal control. As said in section 4.2, our work on this problem is based on experiments conducted in Prof. S. Glaser in Munich, see [29].

6.1.1. Theoretical aspects

Participants: Bernard Bonnard, John Marriott, Monique Chyba [University of Hawaii], Gautier Picot [University of Hawaii], Olivier Cots, Jean-Baptiste Caillaud.

This is done in collaboration with University of Hawaii, and deals with many theoretical aspects of the contrast problem in NMR: analysis of the optimal flow [5], feedback classification in relation with the relaxation times of the species [10], [4]. John Marriott defended his PhD thesis on this topic, on August 28, 2013.

6.1.2. Numerical aspects

Participants: Bernard Bonnard, Jean-Baptiste Caillaud, Olivier Cots, Mathieu Claeys [LAAS CNRS, Toulouse], Pierre Martinon [COMMANDS team, Inria].

We performed, in a collaboration with Pierre Martinon (COMMANDS team, Inria) and Mathieu Claeys (LAAS CNRS, Toulouse), a thorough comparison of the various available numerical methods in optimal control on this important physical problem. Direct and indirect methods (implemented in the **Bocop** and **Hampath** softwares) were tested in the contrast problem, and LMI techniques were used to obtain global bounds on the extremum (in the contrast problem there are many local optima and the global optimality is a complicated issue). This successful collaboration is accounted for in [15] and was presented at the CDC conference [12].

6.2. Conjugate and cut loci computations and applications

Participants: Bernard Bonnard, Olivier Cots, Jean-Baptiste Caillaud.

One of the most important results obtained by B. Bonnard and his collaborators concern the explicit computations of conjugate and cut loci on surfaces. This has obvious applications in optimal control to compute the global optimum; it is also relevant in optimal transport where regularity properties of the transport map in the Monge problem is related to convexity properties of the tangent injectivity domains.

In [3], we complete the previous results obtained in [27] (we bring them from ellipsoids to general revolutions surfaces).

The conjugate and cut loci in Serret-Andoyer metrics and dynamics of spin particles with Ising coupling are analyzed in [7], this is a first step towards the computation of conjugate and cut loci on left invariant Riemannian and sub Riemannian metrics in $SO(3)$ with applications for instance to the attitude control problem of a spacecraft.

An analysis of *singular* metrics on revolution surfaces, motivated by the average orbital transfer problem when the thrust direction is restricted, is proposed in [2].

Finally, [8] determines cut and conjugate loci in an energy minimizing problem that is related to the quantum systems mentioned in the first paragraph of section 4.2.

6.3. Averaging in control

Participants: Bernard Bonnard, Helen-Clare Henninger, Jean-Baptiste Pomet.

A paper on the construction and properties of an “average control system” [1] appeared this year, it is based on Alex Bombrun’s doctoral work (2007). It connects solutions of highly oscillating control systems to those of an average control system, when the frequency of oscillation goes high. It also gives a better ground to averaging for minimum time.

This average system in the case of minimum time for low thrust orbit transfer in the two body problem is currently being explored, in particular the study of its inherent singularities. In [16] we give some properties of this system, like geodesic convexity, and compare it with the one obtained for minimum energy, and Helen Henninger’s PhD aims at going further in this direction and then apply this local study to real missions, possibly in a three-body environment.

6.4. Optimal transport

Participants: Ludovic Rifford, Alice Erlinger, Alessio Figalli [U. of Texas at Austin, USA], Thomas Gallouet [Inria, SIMPAF team], Bernard Bonnard, Jean-Baptiste Caillau, Lionel Jassionnesse, Robert Mc Cann [U. of Toronto].

- The very general condition for continuity of the transport map given in [41] motivated exploration of conditions for convexity of the tangent injectivity domain [42], [3]. Lionel Jassionnesse’s PhD is in part devoted to Ma-Trudinger-Wang tensor that also plays an important role in this matter. Ludovic Rifford has an ongoing collaboration with Alessio Figalli and Thomas Gallouet on the link between this MTW tensor and the convexity of injectivity domains; They already improved a result by Loeper and Villani (the preprint “Ma-Trudinger-Wang condition vs. convexity of injectivity domains” is available from the authors) and aim at proving a conjecture due to Villani, that would hold in the case of analytic surfaces.
- The goal of Alice Erlinger’s PhD, joint with University of Toronto, is to explore Optimal Transport’s application to modeling in economics. She unfortunately stopped her PhD, but some results have already been obtained.

6.5. Applications of control methods to dynamical systems

Participants: Gonzalo Contreras, Alessio Figalli, Ayadi Lazrag, Ludovic Rifford, Raffael Ruggiero.

Ludovic Rifford and collaborators have been applying with success, techniques from geometric control theory to open problems in dynamical systems, mostly on genericity properties and using controllability methods to build suitable perturbations.

This has been applied to closing geodesics [64]. Ayadi Lazrag’s PhD also deals with such problems; applying techniques close to these in [65], one goal is to establish a version of Franks’ lemma for geodesic flows and to apply this to persistence problems. The approach relies on control theory results, with order 2 conditions. See [18] and another preprint (“Franks’ lemma for C^2 -Mañé perturbations of Riemannian metrics and applications to persistence” by Lazrag, Rifford and Ruggiero, available from the authors).

In [17], a non trivial conjecture on generic hyperbolicity of the so-called Aubry set of a Hamiltonian is solved on compact surfaces and in the C^2 topology (for genericity).

NACHOS Project-Team

6. New Results

6.1. Discontinuous Galerkin methods for Maxwell's equations

6.1.1. $DGTD-\mathbb{P}_p$ method based on hierarchical polynomial interpolation

Participants: Loula Fezoui, Stéphane Lanteri.

The DGTD (Discontinuous Galerkin Time Domain) method originally proposed by the team for the solution of the time domain Maxwell's equations [16] relies on an arbitrary high order polynomial interpolation of the component of the electromagnetic field, and its computer implementation makes use of nodal (Lagrange) basis expansions on simplicial elements. The resulting method is often denoted by $DGTD-\mathbb{P}_p$ where p refers to the interpolation degree that can be defined locally i.e. at the element level. In view of the design of a hp -adaptive DGTD method, i.e. a solution strategy allowing an automatic adaptation of the interpolation degree p and the discretization step h , we now investigate alternative polynomial interpolation and in particular those which lead to hierarchical or/and orthogonal basis expansions. Such basis expansions on simplicial elements have been extensively studied in the context of continuous finite element formulations (e.g. [59]) and have thus been designed with global conformity requirements (i.e. H_1 , $H(\text{rot})$ or (div)) whose role in the context of a discontinuous Galerkin formulation has to be clarified. This represents one of the objectives of this study. This year, we have started the development of a new software platform in Fortran 95 implementing $DGTD-\mathbb{P}_p$ able to deal with different polynomial basis expansions on a tetrahedral element, for the solution of the 3D time domain Maxwell equations.

6.1.2. $DGTD-\mathbb{P}_p\mathbb{Q}_k$ method on multi-element meshes

Participants: Clément Durochat, Stéphane Lanteri, Raphael Léger, Claire Scheid, Mark Loriot [Distene, Pôle Teratec, Bruyères-le-Chatel].

In this work, we study a multi-element DGTD method formulated on a hybrid mesh which combines a structured (orthogonal) discretization of the regular zones of the computational domain with an unstructured discretization of the irregularly shaped objects. The general objective is to enhance the flexibility and the efficiency of DGTD methods for large-scale time domain electromagnetic wave propagation problems with regards to the discretization process of complex propagation scenes. With this objective in mind, we have designed and analyzed a $DGTD-\mathbb{P}_p\mathbb{Q}_k$ method formulated on non-conforming hybrid quadrangular/triangular meshes (2D case) or non-conforming hexahedral/tetrahedral meshes (3D case) for the solution of the time domain Maxwell's equations [23]-[22].

6.1.3. $DGTD-\mathbb{P}_p$ method for Debye media and applications to bioelectromagnetics

Participants: Claire Scheid, Maciej Klemm [Communication Systems & Networks Laboratory, Centre for Communications Research, University of Bristol, UK], Stéphane Lanteri.

This work is undertaken in the context of a collaboration with the Communication Systems & Networks Laboratory, Centre for Communications Research, University of Bristol (UK). This laboratory is studying imaging modalities based on microwaves with applications to dynamic imaging of the brain activity (Dynamic Microwave Imaging) on one hand, and to cancerology (imaging of breast tumors) on the other hand. The design of imaging systems for these applications is extensively based on computer simulation, in particular to assess the performances of the antenna arrays which are at the heart of these systems. In practice, one has to model the propagation of electromagnetic waves emitted from complex sources and which propagate and interact with biological tissues. In relation with these issues, we study the extension of the $DGTD-\mathbb{P}_p$ method originally proposed in [16] to the numerical treatment of electromagnetic wave propagation in dispersive media. We consider an approach based on an auxiliary differential equation modeling the time evolution of the electric polarization for a dispersive medium of Debye type (other dispersive media will be considered subsequently). The stability and a priori convergence analysis of the resulting $DGTD-\mathbb{P}_p$ method has been studied [25], and its application to the simulation of the propagation in realistic geometrical models of head tissues is underway in the context of our participation to the DEEP-ER FP7 project.

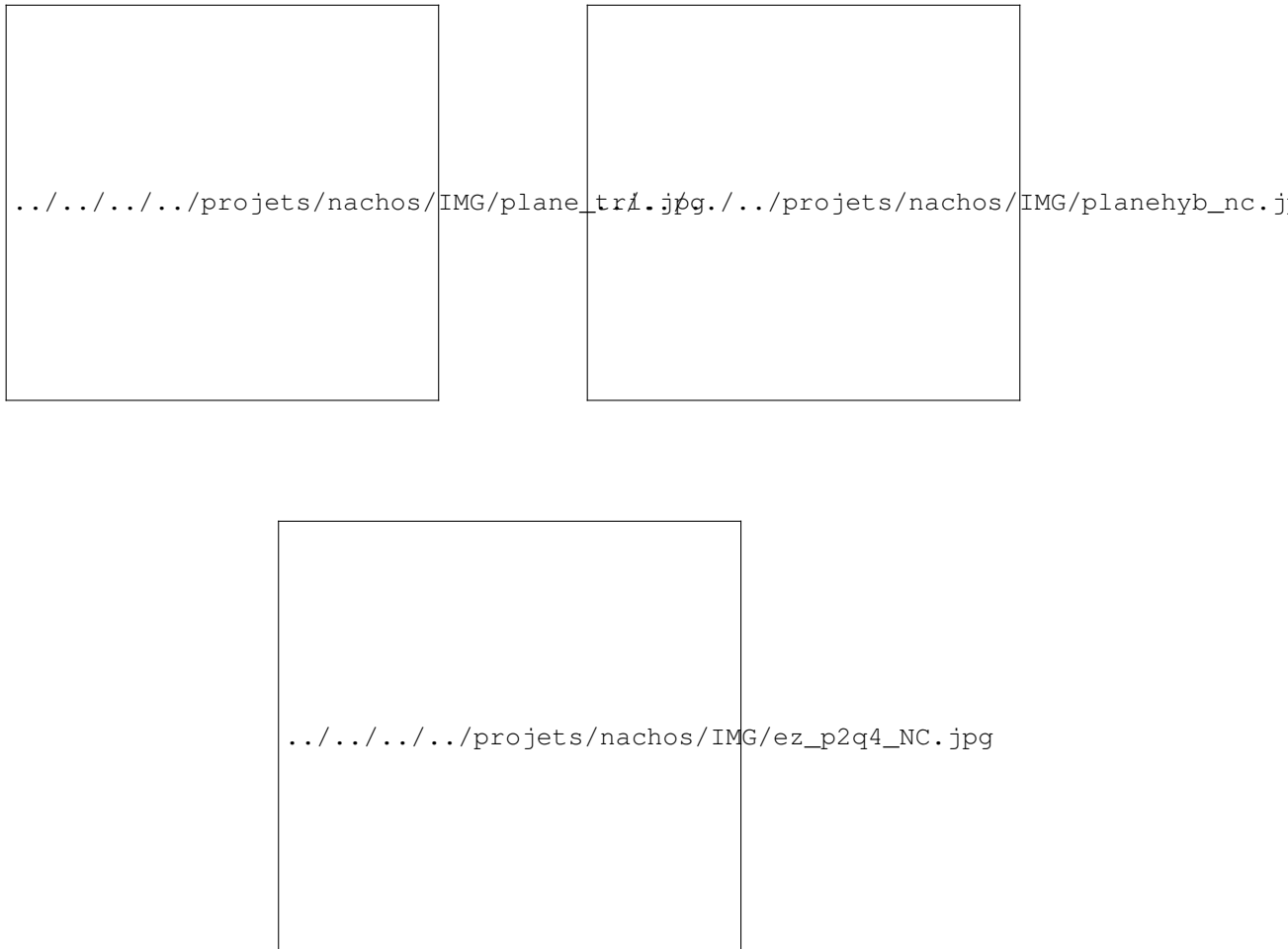


Figure 4. Scattering of a plane wave by a disk. Conforming triangular mesh (top left) and non-conforming quadrangular/triangular mesh (top right). Contour lines of electrical field component E_z from a simulation with a DGTD- $\mathbb{P}_2\mathbb{Q}_4$ method (bottom).

6.1.4. DGTD- \mathbb{P}_p method for nanophotonics

Participants: Claire Scheid, Maciej Klemm [Communication Systems & Networks Laboratory, Centre for Communications Research, University of Bristol, UK], Stéphane Lanteri, Raphael Léger, Jonathan Viquerat.

Modelling and numerical simulation aspects are crucial for a better understanding of nanophotonics. Media that one encounters are complex and the geometries quite involved, so that while a FDTD method failed to be accurate enough, a non conforming discretisation method seems to be well adapted. In this direction, since the end of 2012, we are actively studying the numerical modeling of electromagnetic wave interaction with nanoscale metallic structures. In this context, one has to take into account the dispersive characteristics of metals in the frequency range of interest to nanophotonics. As a first step in this direction, we have considered an auxiliary differential equation approach for the numerical treatment of a Drude, Drude-Lorentz and a generalized dispersion models in the framework of a DGTD- \mathbb{P}_p method [20]-[36]. We performed the corresponding numerical analysis as well as numerical validation tests cases. Some methodological improvements, such as curvilinear elements and higher order time discretization schemes are also underway.

6.1.5. Frequency domain hybridized DGFD- \mathbb{P}_p methods

Participants: Stéphane Lanteri, Liang Li [Faculty Member, School of Mathematical Sciences, Institute of Computational Science, University of Electronic Science and Technology of China Chengdu, China], Ronan Perrussel [Laplace Laboratory, INP/ENSEEIH/UPS, Toulouse].

For certain types of problems, a time harmonic evolution can be assumed leading to the formulation of the frequency domain Maxwell equations, and solving these equations may be more efficient than considering the time domain variant. We are studying a high order Discontinuous Galerkin Frequency Domain (DGFD- \mathbb{P}_p) method formulated on unstructured meshes for solving the 2D and 3D time harmonic Maxwell equations. However, one major drawback of DG methods is their intrinsic cost due to the very large number of globally coupled degrees of freedom as compared to classical high order conforming finite element methods. Different attempts have been made in the recent past to improve this situation and one promising strategy has been recently proposed by Cockburn *et al.* [48] in the form of so-called hybridizable DG formulations. The distinctive feature of these methods is that the only globally coupled degrees of freedom are those of an approximation of the solution defined only on the boundaries of the elements. This work is concerned with the study of such Hybridizable Discontinuous Galerkin (HDG) methods for the solution of the system of Maxwell equations in the time domain when the time integration relies on an implicit scheme, or in the frequency domain. We have been one of the first groups to study HDGFD- \mathbb{P}_p methods based on nodal interpolation methods for the solution of the 2D and 3D frequency domain Maxwell equations [26]-[27].

6.1.6. Exact transparent condition in a DGFD- \mathbb{P}_p method

Participants: Mohamed El Bouajaji, Nabil Gmati [ENIT-LAMSIN, Tunisia], Stéphane Lanteri, Jamil Salhi [ENIT-LAMSIN, Tunisia].

In the numerical treatment of propagation problems theoretically posed in unbounded domains, an artificial boundary is introduced on which an absorbing condition is imposed. For the frequency domain Maxwell equations, one generally use the Silver-Müller condition which is a first order approximation of the exact radiation condition. Then, the accuracy of the numerical treatment greatly depends on the position of the artificial boundary with regards to the scattering object. In this work, we have conducted a preliminary study aiming at improving this situation by using an exact transparent condition in place of the Silver-Müller condition. Promising results have been obtained in the 2D case [30].

6.2. Discontinuous Galerkin methods for the elastodynamic equations

6.2.1. DGTD- \mathbb{P}_p method for viscoelastic media

Participants: Nathalie Glinsky, Stéphane Lanteri, Fabien Peyrusse.

We continue developing high order non-dissipative discontinuous Galerkin methods on simplicial meshes for the numerical solution of the first order hyperbolic linear system of elastodynamic equations. These methods share some ingredients of the DGTD- \mathbb{P}_p methods developed by the team for the time domain Maxwell equations among which, the use of nodal polynomial (Lagrange type) basis functions, a second order leap-frog time integration scheme and a centered scheme for the evaluation of the numerical flux at the interface between neighboring elements. The resulting DGTD- \mathbb{P}_p methods have been validated and evaluated in detail in the context of propagation problems in both homogeneous and heterogeneous media including problems for which analytical solutions can be computed. Particular attention was given to the study of the mathematical properties of these schemes such as stability, convergence and numerical dispersion.

A recent novel contribution is the extension of the DGTD method to include viscoelastic attenuation. For this, the velocity-stress first-order hyperbolic system is completed by additional equations for the anelastic functions including the strain history of the material. These additional equations result from the rheological model of the generalized Maxwell body and permit the incorporation of realistic attenuation properties of viscoelastic material accounting for the behaviour of elastic solids and viscous fluids. In practice, we need solving $3L$ additional equations in 2D (and $6L$ in 3D), where L is the number of relaxation mechanisms of the generalized Maxwell body. This method has been implemented in 2D and validated by comparison to results obtained by a finite-difference method, in particular for wave propagation in a realistic basin of the area of Nice (south of France)

6.2.2. DGTD- \mathbb{P}_p method for the assessment of topographic effects

Participants: Etienne Bertrand [CETE Méditerranée], Nathalie Glinsky.

This study addresses the numerical assessment of site effects especially topographic effects. The study of measurements and experimental records proved that seismic waves can be amplified at some particular locations of a topography. Numerical simulations are exploited here to understand further and explain this phenomenon. The DGTD- \mathbb{P}_p method has been applied to a realistic topography of Rognes area (where the Provence earthquake occurred in 1909) to model the observed amplification and the associated frequency. Moreover, the results obtained on several homogeneous and heterogeneous configurations prove the influence of the medium in-depth geometry on the amplifications measures at the surface .

6.2.3. DGTD- \mathbb{P}_p method for arbitrary heterogeneous media

Participants: Nathalie Glinsky, Diego Mercerat [CETE Méditerranée].

We have recently devised an extension of the DGTD method for elastic wave propagation in arbitrary heterogeneous media. In realistic geological media (sedimentary basins for example), one has to include strong variations in the material properties. Then, the classical hypothesis that these properties are constant within each element of the mesh can be a severe limitation of the method, since we need to discretize the medium with very fine meshes resulting in very small time steps. For these reasons, we propose an improvement of the DGTD method allowing non-constant material properties within the mesh elements. A change of variables on the stress components allows writing the elastodynamic system in a pseudo-conservative form. Then, the introduction of non-constant material properties inside an element is simply treated by the calculation, via convenient quadrature formulae, of a modified local mass matrix depending on these properties. This new extension has been validated for a smoothly varying medium or a strong jump between two media, which can be accurately approximated by the method, independently of the mesh .

6.2.4. DGFD- \mathbb{P}_p method for frequency domain elastodynamics

Participants: Hélène Barucq [MAGIQUE3D project-team, Inria Bordeaux - Sud-Ouest], Marie Bonnasse, Julien Diaz [MAGIQUE3D project-team, Inria Bordeaux - Sud-Ouest], Stéphane Lanteri.

We have started this year a research direction aiming at the development of high order discontinuous Galerkin methods on unstructured meshes for the simulation of frequency domain elastodynamic and viscoelastic wave propagation. This study is part of the Depth Imaging Partnership (DIP) between Inria and TOTAL. The PhD thesis of Marie Bonnasse is at the heart of this study which is funded by TOTAL.

6.3. Multiscale finite element methods for time-domain wave models

Participants: Marie-Helene Lallemand Tenkes, Stéphane Lanteri, Claire Scheid, Frédéric Valentin [LNCC, Petrópolis, Brazil].

Mathematical (partial differential equation) models embedding multiscale features occur in a wide range of natural situations and industrial applications involving wave propagation. This is for instance the case of electromagnetic or seismic wave propagation in heterogenous media. Although the related applications take place at the macro-scale, it is well known that the parameters describing the macro-scale processes are eventually determined by the solution behavior at the micro-scale. As a result, each stage of the modeling of the underlying problem is driven by distinct sets of PDEs with highly heterogeneous coefficients and embedded high-contrast interfaces. Because of the huge difference in physical scales in heterogenous media it is not computationally feasible to fully resolve the micro-scale features directly. Macroscopic models or upscaling techniques have therefore to be developed that are able to accurately capture the macroscopic behavior while significantly reducing the computational cost. In this context, researchers at LNCC have recently proposed a new family of finite element methods [51]- [50], called Multiscale Hybrid-Mixed methods (MHM), which is particularly adapted to be used in high-contrast or heterogeneous coefficients problems. Particularly, they constructed a family of novel finite element methods sharing the following properties: (i) stable and high-order convergent; (ii) accurate on coarse meshes; (iii) naturally adapted to high-performance parallel computing; (iv) induce a face-based a posteriori error estimator (to drive mesh adaptativity); (v) locally conservative. We have started this year a new reserach direction aiming at the design of similar MHM methods for solving PDE models of time-domain electromagnetic and seismic wave propagation.

6.4. Time integration strategies and resolution algorithms

6.4.1. Hybrid explicit-implicit DGTD- \mathbb{P}_p method

Participants: Stéphane Descombes, Stéphane Lanteri, Ludovic Moya.

Existing numerical methods for the solution of the time domain Maxwell equations often rely on explicit time integration schemes and are therefore constrained by a stability condition that can be very restrictive on highly refined meshes. An implicit time integration scheme is a natural way to obtain a time domain method which is unconditionally stable. Starting from the explicit, non-dissipative, DGTD- \mathbb{P}_p method introduced in [16], we have proposed the use of Crank-Nicolson scheme in place of the explicit leap-frog scheme adopted in this method [5]. As a result, we obtain an unconditionally stable, non-dissipative, implicit DGTD- \mathbb{P}_p method, but at the expense of the inversion of a global linear system at each time step, thus obliterating one of the attractive features of discontinuous Galerkin formulations. A more viable approach for 3D simulations consists in applying an implicit time integration scheme locally i.e in the refined regions of the mesh, while preserving an explicit time scheme in the complementary part, resulting in an hybrid explicit-implicit (or locally implicit) time integration strategy. In [7], we conducted a preliminary numerical study of a hybrid explicit-implicit DGTD- \mathbb{P}_p method, combining a leap-frog scheme and a Crank-Nicolson scheme, and obtained promising results. More recently, we further investigated two such strategies, both theoretically (especially, convergence in the ODE and PDE senses) [17] and numerically in the 2D case [28]. A last topic is to propose higher order time integration techniques based on the second-order locally implicit method to fully exploit the attractive features of this approach combined with a DG discretisation which allows to easily increase the spatial convergence order. Promising results in 2D reaching high order in time, between 3, 5 and 4, have been obtained in [29] by applying Richardson extrapolation and composition methods.

6.4.2. Optimized Schwarz algorithms for the frequency domain Maxwell equations

Participants: Victorita Dolean, Martin Gander [Mathematics Section, University of Geneva], Stéphane Lanteri, Ronan Perrussel [Laplace Laboratory, INP/ENSEEIH/UPS, Toulouse].

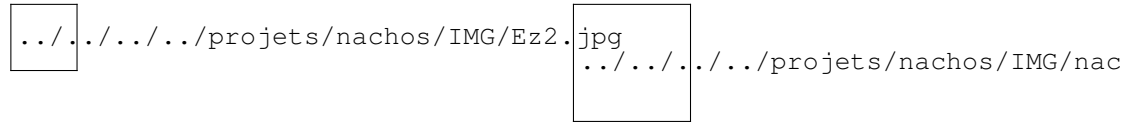


Figure 5. Scattering of a plane wave by an airfoil profile. Contour lines of electrical field component E_z (left) and locally refined triangular mesh with partitioning in explicit/implicit zones (right).

Even if they have been introduced for the first time two centuries ago, over the last two decades, classical Schwarz methods have regained a lot of popularity with the development of parallel computers. First developed for the elliptic problems, they have been recently extended to systems of hyperbolic partial differential equations, and it was observed that the classical Schwarz method can be convergent even without overlap in certain cases. This is in strong contrast to the behavior of classical Schwarz methods applied to elliptic problems, for which overlap is essential for convergence. Over the last decade, optimized versions of Schwarz methods have been developed for elliptic partial differential equations. These methods use more effective transmission conditions between subdomains, and are also convergent without overlap for elliptic problems. The extension of such methods to systems of equations and more precisely to Maxwell's system (time harmonic and time discretized equations) has been studied in [9]. The optimized interface conditions proposed in [9] were devised for the case of non-conducting propagation media. We have recently studied the formulation of such conditions for conducting media [4]. Besides, we have also proposed an appropriate discretization strategy of these optimized Schwarz algorithms in the context of a high order DGFD- \mathbb{P}_p method formulated on unstructured triangular meshes for the solution of the 2D frequency domain Maxwell equations [42].

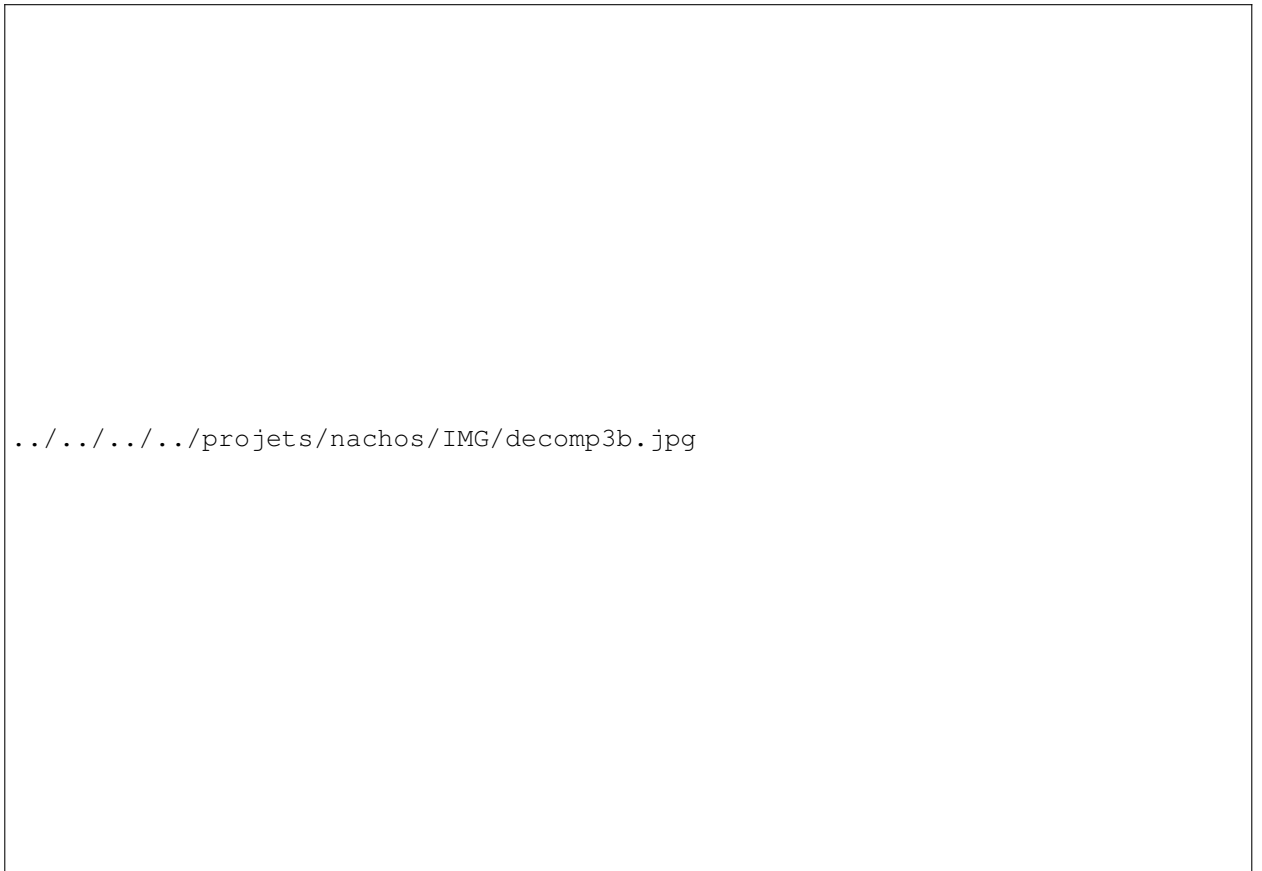


Figure 6. Propagation of a plane wave in a multilayered heterogeneous medium. Problem setting and two-subdomain decomposition (top). Contour lines of the real part of the E_z component of the electrical field (bottom left) and asymptotic convergence of the optimized Schwarz algorithms (bottom right).

OPALE Project-Team

6. New Results

6.1. Mathematical analysis and control of macroscopic traffic flow models

6.1.1. Vehicular traffic

Participants: Alessandra Cabassi, Maria Laura Delle Monache, Paola Goatin, Alexandre Bayen [UC Berkeley, CA, USA], Legesse Lemecha Obsu [Addis Ababa University, Ethiopia].

In collaboration with UC Berkeley, and as part of the Associated Team ORESTE activity (see <http://www-sop.inria.fr/members/Paola.Goatin/ORESTE/index.html>), we have proposed a new junction model for ramp metering: we introduce a coupled PDE-ODE model, in which the PDE describes the evolution of the cars flow on the main lane and the ODE describes the evolution of the queue length on the on-ramp, modeled by a buffer, which ensures that boundary conditions are satisfied in strong sense. We were able to prove existence and uniqueness of the solution of the corresponding Riemann problem [41]. Relying on the above junction model, we have applied the Discrete Adjoint Method to efficiently compute (locally) optimal ramp-metering parameters to minimize the total travel time on a stretch of highway [80].

In parallel, we have proposed two optimization strategy for instantaneous optimization of total travel times and total waiting times at roundabouts, which give an estimate of the time spent by drivers on the network section. These cost functionals are minimized with respect to the right-of-way parameter of the incoming roads. For each cost functional, the analytical expression is given for each junction, see [72]. This work is part of L.L. Obsu's PhD thesis.

Finally, we designed a new finite volume algorithm to track the trajectory of a bus in the surrounding traffic using a locally non-uniform moving mesh, see [3, 4, 5].

As part of our TRAM3 activity, we also organized the workshop "TRAM2 - Traffic Modeling and Management: Trends and Perspectives", which successfully took place at Inria Sophia Antipolis on March 20-22, 2013 (see <https://team.inria.fr/opale/workshop-tram2/>).

In the framework of the EIT ITC Labs Multimodal Mobility activity, A. Cabassi's internship was devoted to the calibration and the validation of a first order traffic flow model against processed real data provided by the industrial partners Autoroutes Traffic and VINCI Autoroutes, see [69].

6.1.2. Crowd motion

Participants: Régis Duvigneau, Paola Goatin, Matthias Mimault, Debora Amadori [L'Aquila University, Italy], Christophe Chalons [LJLL, UP7], Massimiliano D. Rosini [ICM, Warsaw University, Poland], Nicolas Seguin [LJLL, UPMC], Monika Twarogowska.

From the analytical point of view, we have been studying the properties of some models in one space dimension. Concerning Hughes' scalar model, we have established a partial existence result in collaboration with D. Amadori and M.D. Rosini (see [75]). M. Mimault's internship in 2012 was devoted to develop a MATLAB code based on wave-front tracking to compute the solutions of Hughes' model with generalized running cost, see [42]. He is currently working on a mixed hyperbolic-elliptic 2x2 system of conservation laws describing two groups of people moving in opposite directions. Finally, in collaboration with C. Chalons and N. Seguin, we generalized previous results on conservation laws with local flux constraints [3], [5] to general flux functions and non-classical solutions arising in pedestrian flow modeling, see [39]. From the numerical point of view, we have implemented some macroscopic models in 2D on unstructured triangular meshes on the Num3sis platform. We provided a comparison between first and second order models in reproducing complex dynamics of crowd motion, such as formation of stop-and-go waves and clogging at bottlenecks. Then, we concentrated on the higher-order model and analyzed the dependence of the behavior of its solutions on some of the parameters of the system. In particular, we produced some examples where placing obstacles in front of the door prevents from blocking and decreases the evacuation time, see [73], [81].

The above researches were partially funded by the ERC Starting Grant "TRAM3 - Traffic management by macroscopic models".

6.2. Optimum design and control in fluid dynamics and its couplings

In computational sciences for physics and engineering, Computational Fluid Dynamics (CFD) are playing one of the major roles in the scientific community to foster innovative developments of numerical methodologies. Very naturally, our expertise in compressible CFD has led us to give our research on numerical strategies for optimum design a particular, but not exclusive focus on fluids.

The framework of our research aims to contribute to numerical strategies for PDE-constrained multi-objective optimization, with a particular emphasis on CPU-demanding computational applications in which the different criteria to be minimized (or reduced) originate from different physical disciplines that share the same set of design variables. These disciplines are often fluids, as a primary focus, coupled with some other disciplines, such as structural mechanics.

Our approach to *competitive optimization* is focused on the two-discipline problem. It is based on a particular construction of *Nash games*, relying on a *split of territory* in the assignment of individual strategies. A methodology has been proposed for the treatment of two-discipline optimization problems in which one discipline, the primary discipline, is preponderant, or fragile. Then, it is recommended to identify, in a first step, the optimum of this discipline alone using the whole set of design variables. Then, an orthogonal basis is constructed based on the evaluation at convergence of the Hessian matrix of the primary criterion and constraint gradients. This basis is used to split the working design space into two supplementary subspaces to be assigned, in a second step, to two virtual players in competition in an adapted Nash game, devised to reduce a secondary criterion while causing the least degradation to the first. The formulation has been proved to potentially provide a set of Nash equilibrium solutions originating from the original single-discipline optimum point by smooth continuation, thus introducing competition gradually [53]. (see also subsection `subject:helico`).

Our approach to *cooperative optimization*, in theory, is not limited in number of objective functions. It is based on a result of convex analysis established for a general unconstrained multi-objective problem in which all the gradients are assumed to be known. The theorem [16] states that in the convex hull of the gradients, there exists a unique vector of minimal norm, ω ; if it is nonzero, the vector ω is a descent direction common to all criteria; otherwise, the current design point is Pareto-stationary. This result led us to generalize the classical steepest-descent algorithm by using the vector ω as search direction. We refer to the new algorithm as the multiple-gradient descent algorithm (MGDA). The MGDA yields to a Pareto-stationary point, and actual Pareto-optimality is then tested [54] (see also subsection 6.2.4).

The two approaches have been combined to explore the Pareto front segment-wise as illustrated on Figure 2.

6.2.1. Multiple-Gradient Descent Algorithm (MGDA)

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Matteo Giacomini, Abderrahmane Habbal, Adrien Zerbinati.

6.2.1.1. Theory and numerical experimentation of the MGDA construction

In multi-objective optimization, the knowledge of the Pareto set provides valuable information on the reachable optimal performance. A number of evolutionary strategies (PAES, NSGA-II, etc), have been proposed in the literature and proved to be successful to identify the Pareto set. However, these derivative-free algorithms are very demanding in terms of computational time. Today, in many areas of computational sciences, codes are developed that include the calculation of the gradient, cautiously validated and calibrated.

The notion of Pareto-stationarity, originally established to be a necessary condition of optimality in differentiable multi-objective optimization of unconstrained problems, has been extended to problems subject to equality constraints. On this basis, we were able to establish that by augmenting, in a classical manner, the objective-functions of a penalty term equal to the square of the constraint violation, and applying the standard MGDA to it, would result in converged solutions that are Pareto-stationary in the extended sense. Numerical experimentation on this is on-going.



Figure 2. Two-discipline optimization of a generic geometry of a supersonic aircraft, for concurrent drag and sonic-boom reduction (from A. Minelli's doctoral thesis). The wave drag is calculated by the ONERA elsA code in 3D finite-volume Eulerian flow mode over a 6M-node mesh and the sonic boom using a three-layer approach. The Nash-game paths have been devised by appropriate territory splitting in order to be tangent to the Pareto front, and they are interrupted whenever the Pareto-stationarity condition is judged excessively violated. The MGDA paths converge rapidly back to the front. The simulation demonstrates how the two algorithms complement each other and provide a potential for a piecewise description of the Pareto front, evaluated more economically than a stochastic algorithm operating on a large population.

6.2.1.2. Meta-model-assisted CFD optimization by MGDA

Using MGDA in a multi objective optimization problem requires the evaluation of a large number of points with regard to criteria, and their gradients. In the particular case of a CFD problems, each point evaluation is very costly since it involves a flow computation, possibly the solution of an adjoint-equation. To alleviate this difficulty, we have proposed to construct meta-models of the functionals of interest (lift, drag, etc) and to calculate approximate gradients by local finite differences. These meta-models are updated throughout the convergence process to the evaluation of the new design points by the high-fidelity model, here the 3D compressible Euler equations.

This variant of MGDA has been tested successfully over a problem of external aerodynamic optimum-shape design of an aircraft wing consisting of reducing wave-drag, and augmenting lift. After only a few cycles of database updates, the Pareto front visibly forms, and this result is achieved at a very moderate computational cost [68]. This variant has been extended successfully to an internal flow optimization problem related to an automobile air-conditioning system and governed by the Navier-Stokes equations. This more difficult problem has been proposed by Renault within the OMD2 ANR project. These studies have been reported in A. Zerbinati's doctoral thesis [38].

6.2.1.3. Exact shape gradients

MGDA has successfully been tested over a two-objective optimization problem governed by two-dimensional elasticity. The deformation of a plate is calculated using an isogeometric approximation (see 6.3) and compliance derived from it. The exact parametric shape gradient is calculated, yielding the gradient of the objective function in two antagonistic situations differing by the loading. Pareto-fronts are thus identified.

6.2.1.4. Perspectives

MGDA offers the possibility to handle in a rational way several objective-functions for which gradients are known or approximated concurrently. This potential opens methodological paths to several themes of interest in high-fidelity simulation-based optimization: optimization of complex systems whose performance is evaluated w.r.t. several criteria originating from different, coupled disciplines; optimization under uncertainties, by introducing sensitivities as additional objectives; optimization of time-dependent systems, such as optimization of flow-control devices that generate a periodic flow (see next subsection), by converting the problem into a multi-point problem by time-discretization of the time and parameter-dependent functional; etc.

6.2.2. Flow control

Participants: Régis Duvigneau, Jérémie Labroquère, Emmanuel Guilmineau [Ecole Centrale de Nantes].

Shape optimization methods are not efficient to improve the performance of fluid systems, when the flow is characterized by a strong unsteadiness related to a massive detachment. This is typically the case for the flow around an automotive body or a wing in stall condition. To overcome this difficulty, flow control strategies are developed, that aim at manipulating vortex dynamics by introducing some active actuators, such as periodic blowing/suction jets. In this context, the choice of the control parameters (location, amplitude, frequency) is critical and not straightforward. Therefore, we develop a methodology to determine optimal control parameters by coupling the simulation of unsteady actuated flows with optimization algorithms. Two research axes have been considered :

- the resolution of the unsteady sensitivity equations derived from the state equations, to exhibit the dependency of the flow dynamics with respect to the control ;
- the optimization of control parameters using a statistical metamodel-based strategy.

In this perspective, unsteady Reynolds Averaged Navier-Stokes equations are solved, with some turbulence closures. Different models for synthetic jet have been implemented to simulate the actuation, and then validated for different turbulence closures [70].

Specific developments have been carried out in the metamodel-based optimizer to include a noise term into Gaussian Process model, which is used to filter errors arising from unsteady simulations. A systematic assessment of modeling and numerical errors has been archived [57], for a backward facing step test-case, with the objective of controlling the re-attachment point location.

This activity is conducted in collaboration with the CFD team of Ecole Centrale de Nantes.

6.2.3. Robust design

Participants: Jean-Antoine Désidéri, Régis Duvigneau, Daigo Maruyama.

This work aims at developing robust design tools for aircraft w.r.t. aerodynamic performance subject to uncertainties, arising from geometrical features and fluctuations of inflow conditions. The robust design process is considered as a multi-objective optimization problem, which consists in minimizing or maximizing statistical moments of the cost function.

In the context of airfoil design, MGDA is used to improve simultaneously the mean and variance of the lift and drag coefficients, yielding a four-objective optimization problem [71].

6.2.4. Sonic boom reduction

Participants: Gérald Carrier [Research Engineer, ONERA/DAAP], Jean-Antoine Désidéri, Andrea Minelli, Itham Salah El Din [Research Engineer, ONERA/DAAP].

When an aircraft flies at supersonic speed, it generates at ground level an N-shaped shock structure which can cause serious environmental damage (“sonic boom”). Thus a problem of interest in aerodynamic optimization is to design such an aircraft to reduce the intensity of the sonic boom while maintaining the aerodynamic performance (drag minimization under lift constraint). Andrea Minelli aimed at contributing to this two-discipline optimization problem. In the first part of his work, an inverse problem has been formulated and solved for “shaped sonic boom” and found in excellent agreement with the George-Seebass-Darden theory [82] for the calculation of the Whitham function corresponding to the lowest-boom (axisymmetric) shape. Method and results have been generalized to more general geometries and have been presented internationally in [58].

Besides, aero-acoustic optimizations have been realized successfully by coupling the aerodynamic optimizer (based on Euler calculations by the elsA software) with the sonic-boom computation in a Nash game formulation. These experiments, conducted with our optimization platform FAMOSA, have demonstrated that starting from the shape optimized aerodynamically, one could retrieve smoothly a shape corresponding to nearly-optimal sonic-boom reduction [36]. and [54].

6.2.5. Helicopter rotor blade optimization in both situations of hovering and forward flight

Participants: Michel Costes [Research Engineer, ONERA/DAAP], Jean-Antoine Désidéri, Arnaud Le Pape [Research Engineer, ONERA/DAAP], Enric Roca Leon.

E. Roca Leon is conducting a CIFRE thesis supported by EUROCOPTER (Marignane) at ONERA DAAP. This thesis follows the doctoral thesis of A. Dumont in which the adjoint-equation approach was used to optimize a rotor blade in hovering flight. The goal of this new thesis is to solve a two-objective optimization problem in which the hovering-flight criterion is considered preponderant, but a new criterion that takes into account the forward-flight situation is also introduced, concurrently. The second criterion is the power necessary to maintain the forward motion. The first phase of thesis work has been devoted to the set up of a hierarchy of models from low to high fidelity, in order to calibrate appropriate functional criteria. Then, actual two-objective optimizations are conducted via our Nash game approach to competitive optimization with territory splitting based on reduced Hessian diagonalization. A first successful experiment has been realized in which 16 geometrical parameters have been optimized to reduce the power in forward motion while maintaining sub-optimality of the drag in hover. These results have been accepted for presentation at the American Helicopter Society Forum [62], and [53].

6.2.6. Optimum design in naval hydrodynamics

Participants: Régis Duvigneau, Louis Blanchard, Elisa Berini [K-Epsilon company].

Naval hydrodynamics field has recently shown a growing interest for optimum design methods. The computational context is especially complex because it implies unsteady two-phase turbulent flows, with possibly very high Reynolds number (up to 10^9). The use of automated design optimization methods for such problems requires new developments to take into account the large CPU time necessary for each simulation and the specificity of the geometries considered.

Some developments have been initiated on the geometrical modelling of hull shapes by parametric surfaces. The objective was to be able to modify existing hull shapes by controlling a small number of parameters, that are meaningful for naval architects. We have considered as test-case the bow shape for trawler ships. As a second step, an optimum shape procedure has been set up, based on a metamodel-based optimizer, the developed CAD model and the simulation tool for free-surface flows provided by K-Epsilon company. The objective was to reduce the wave drag of a trawler ship by adding a bow, whose parameters are optimized [50].

6.3. Isogeometric analysis and design

Participants: Régis Duvigneau, Bernard Mourrain [Galaad project-team], Alexandros Ginnis [Nat. Tech. Univ. of Athens], Bernd Simeon [Tech. Univ. of Kaiserslautern], Gang Xu [Hangzhou Dianzi Univ.].

Design optimization stands at the crossroad of different scientific fields (and related software): Computer-Aided Design (CAD), Computational Fluid Dynamics (CFD) or Computational Structural Dynamics (CSM), parametric optimization. However, these different fields are usually not based on the same geometrical representations. CAD software relies on Splines or NURBS representations, CFD and CSM software uses grid-based geometric descriptions (structured or unstructured), optimization algorithms handle specific shape parameters. Therefore, in conventional approaches, several information transfers occur during the design phase, yielding approximations that can significantly deteriorate the overall efficiency of the design optimization procedure. Moreover, software coupling is often cumbersome in this context.

The isogeometric approach proposes to definitely overcome this difficulty by using CAD standards as a unique representation for all disciplines. The isogeometric analysis consists in developing methods that use NURBS representations for geometric modeling, computational domain description and solution basis functions. Using such a unique data structure allows to compute the solution on the exact geometry (not a discretized geometry), obtain a more accurate solution (high-order approximation), reduce spurious numerical sources of noise that deteriorate convergence, avoid data transfers between the software. Moreover, NURBS representations are naturally hierarchical and allows to define multi-level algorithms for solvers as well as optimizers.

In this context, some studies on elliptic problems have been conducted in collaboration with the Galaad project-team and Hangzhou Dianzi University, such as the development of methods for adaptive parameterization including an a posteriori error estimate [46], [47], [48]. A collaborative work has also been carried out with the Technical University of Kaiserslautern, concerning the computation of shape gradients for linear elasticity problems, and with the National Technical University of Athens for hull shape optimization [55].

6.4. Optimum design in structural mechanics

6.4.1. Shape Optimization in Multidisciplinary Non-Linear Mechanics

Participants: Aalae Benki, Jean-Antoine Désidéri, Abderrahmane Habbal, Gael Mathis [ArcelorMittal, CRAA].

In collaboration with the ArcelorMittal's Center for Research in Automotive and Applications (CRAA), we study the multidisciplinary shape and parameter design of highly non linear mechanical 2D and 3D structures. We have developed methods adapted to the approximation of Pareto Fronts such as Normal Boundary Intersection NBI and Normalized Normal Constraint Method NNCM. Due to the time consuming cost evaluation, the use of cheap to evaluate surrogate models is mandatory. We have studied the consistency of the approach NBI or NNCM plus surrogates, which turned out to be successful for a broad panel of standard mathematical benchmarks. The coupling is successfully applied to a small scale industrial case, namely the shape optimization of a can bottom vis à vis dome reversal pressure and dome growth criteria. We have

then defined a Nash game between criteria where the latter are approximated by the RBF metamodels. First, we validated the computation of a Nash equilibrium for mathematical functions, then we computed Nash equilibria for the small scale industrial case of the shape optimization of the can bottom.

Then, we considered the 3D problem of an automotive twist beam. In this 3D case, we aim to Pareto-optimal shapes for two objectives, the first being to minimize the Von-Mises strain to guarantee the formability of the twist beam, and the second being to maximize the stiffness. For solution with higher stiffness than the initial one, we could decrease the thickness to obtain a mass reduction with the same end-user properties.

We also introduced, to our knowledge for the first time in the structural optimization area, the notion of Kalai-Smorodinsky equilibria which is aimed at the selection of equilibria among Pareto-optimal solutions. We applied this notion of equilibria to both industrial cases, and compared the results to Nash equilibria. [56] [64]



Figure 3. Concurrent design in industrial applications. A packaging problem of commercial cans (left). Automotive twist beam (right)

6.4.2. Optimization of Addendum Surfaces in Stamping

Participants: Fatima Zahra Oujebbour, Rachid Ellaia, Abderrahmane Habbal, Ziheng Zhao.

Within the OASIS Consortium (ArcelorMittal, ErDF, Inria, UTC, EURODECISION, ESILV, NECS, DeltaCAD, SCILAB-DIGITEO), the Opale project-team leads the Optimization task. Our aim is to develop decentralized decision-making algorithms dedicated to find efficient solutions (Pareto optimal) in a complex multi-disciplinary framework (forming, stamping, welding non-linear processes, spring-back, vibration, in-function linear processes, crash and fatigue non linear and non differentiable processes) for several (between three and five) criteria. An important difficulty when trying to identify the Pareto Front, even when using adapted methods such the Normal Boundary Intersection, is that the criteria involved (thanks to the high nonlinearity in the mechanical models) exhibit many local optima. So one must use global optimization methods. We have studied the hybrid approach Simulated Annealing with Simultaneous Perturbation SASP for a suite of mathematical test-cases. To envisage the application of our method to the complex CPU time consuming stamping process, we lead an intermediate phase dedicated to the validation of the SASP method for the minimization of the spring-back that follows the stamping of a metal sheet, the design variable being the process parameters (two then four parameters). Then, we considered the more complex shape design of the initial blank. The initial

blank design is a critical step in stamping design procedure, therefore it should be optimally designed. Our aim is to find the optimal initial blank shape that avoids or at least minimizes the springback and failure flaws. For this study, the geometry of the blank contour is described by parametric spline curves. Seven control points (P1,...,P7) are used to define the spline curves in order to have a wide variety of geometries. The exact computational evaluation of our criteria, springback and failure, is very expensive (the FE model request around 45 min to predict these two criteria) and the design space is of quite high dimension. Therefore, we considered the recourse to the sparse grid interpolation. Optimization process based on sparse grid interpolation is an optimal alternative in which criteria can be approximated with a suitable interpolation formula that needs significantly less points than the full grid. The obtained metamodel using sparse grid interpolation needs less than 1s to predict springback and failure on the same computation machine. To find the optimal initial blank shape, it was decided to perform the optimization process using the obtained metamodel. The construction of the sparse grid interpolant was based on the Chebyshev Gauss-Lobatto grid type and using the polynomial basis functions. This technique achieves a good accuracy with a competitive number of grid points. The comparison of the obtained fronts shows that we can capture Pareto solutions by NBI and NNCM with fewer points than NSGAII which requires a large number of populations and several generations to obtain the Pareto front. [60] [61] [63] [77]



Figure 4. Multiobjective design of the stamping process of a high performance steel sheet. The design variable is the initial blank shape, and the costs are elastic spring-back and failure. Sparse grid approximation of the costs is used. The Pareto front obtained by NBI and NNCM (lower-left) are compared to a NSGA-II one (lower-right).

6.5. Application of shape and topology design to biology and medicine

6.5.1. Assessing the ability of the 2D Fisher-KPP equation to model cell-sheet wound closure

Participants: Abderrahmane Habbal, H  l  ne Barelli [Univ. Nice Sophia Antipolis, CNRS, IPMC], Gr  goire Malandain [Inria, EPI Morpheme].

We address in this joint collaboration the ability of the widely used Fisher-KPP equations to render some of the dynamical features of epithelial cell-sheets during wound closure.

Our approach is based on nonlinear parameter identification, in a two-dimensional setting, and using advanced 2D image processing of the video acquired sequences. As original contribution, we lead a detailed study of the profiles of the classically used cost functions, and we address the "wound constant speed" assumption, showing that it should be handled with care.

We study five MDCK cell monolayer assays in a reference, activated and inhibited migration conditions. Modulo the inherent variability of biological assays, we show that in the assay where migration is not exogeneously activated or inhibited, the wound velocity is constant. The Fisher-KPP equation is able to accurately predict, until the final closure of the wound, the evolution of the wound area, the mean velocity of the cell front, and the time at which the closure occurred. We also show that for activated as well as for inhibited migration assays, many of the cell-sheet dynamics cannot be well captured by the Fisher-KPP model. Original unexplored utilizations of the model such as wound assays classification based on the calibrated diffusion and proliferation rate parameters is ongoing.[49] [76]

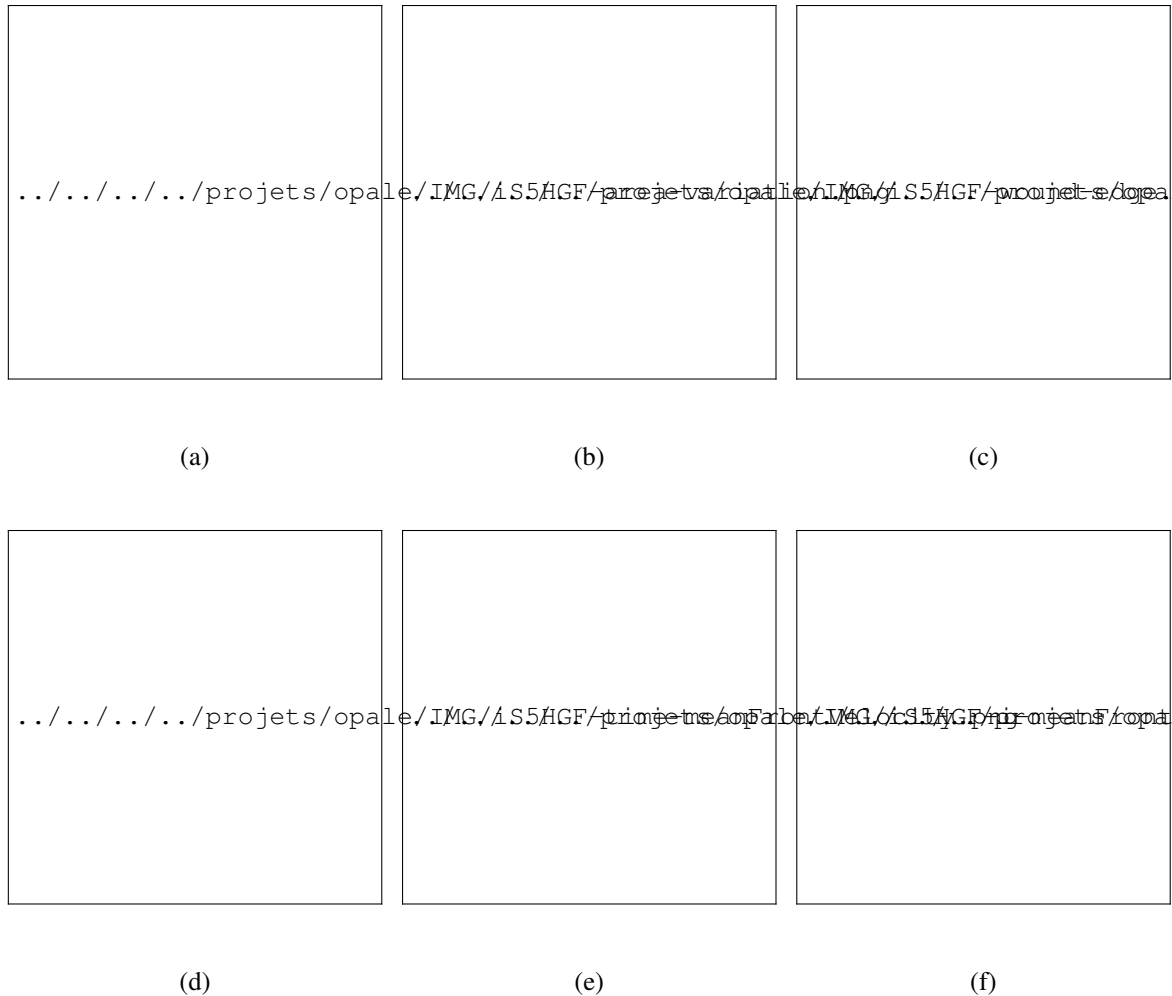


Figure 5. **A regular wound assay** (a) Time evolution of wound area (in pixel). (b) Time evolution of the leading-edge length (in pixel). (c) 3D XT view at first and mid-rows. (d) Mean (in time) velocity of pixels located at the leading edge (in pixel/min). (e) Averaged (in space) leading-edge velocity (in pixel/min). (f) 2D XT view at first and mid-rows.

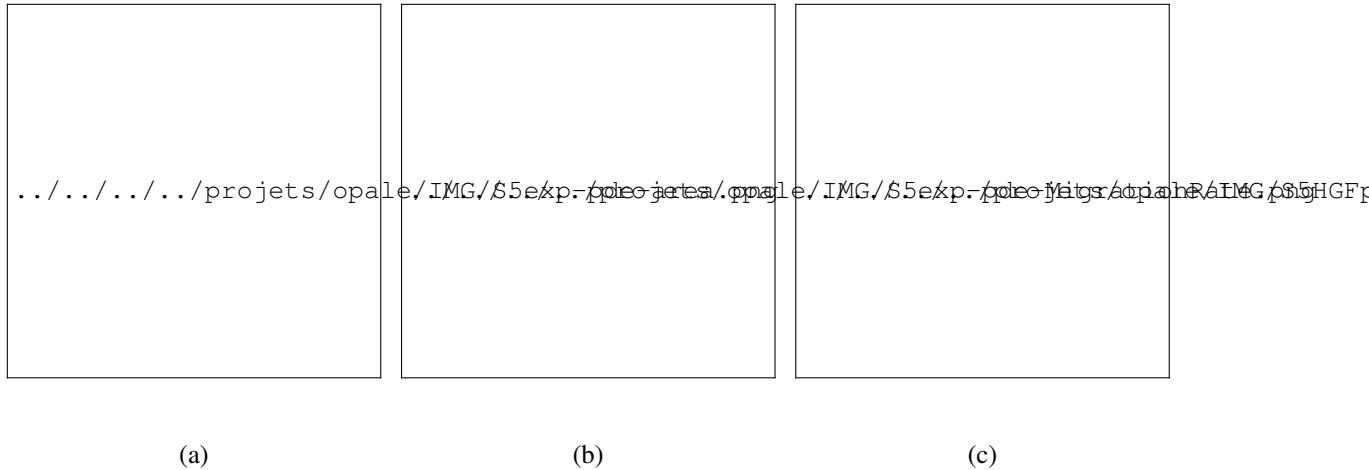


Figure 6. **A regular wound assay. Computational vs experimental wound evolution.** (a) Time variation of experimental (blue) versus computed (red) wound area (in pixel). (b) Time variation of the experimental (blue-dot) versus computed (red) migration rate (in pixel/min). (c) 3D XT view at first and mid-rows.

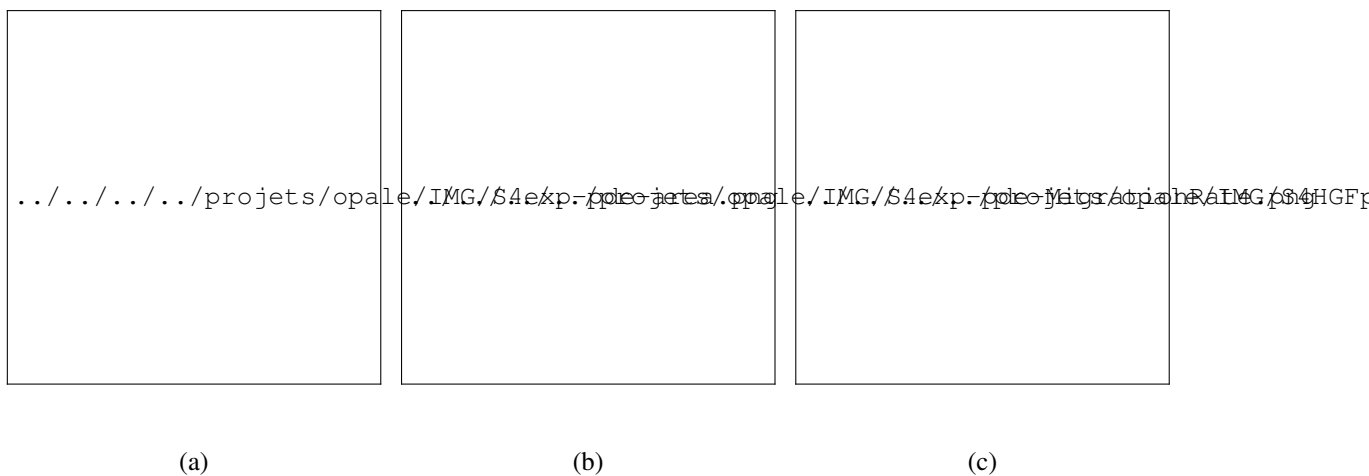


Figure 7. **An accelerating activated wound assay. Computational vs experimental wound evolution.** (a) Time variation of experimental (blue) versus computed (red) wound area (in pixel). (b) Time variation of the experimental (blue-dot) versus computed (red) migration rate (in pixel/min). (c) 3D XT view at first and mid-rows.

SCIPORT Team

6. New Results

6.1. Automatic Differentiation and parallel codes

Participants: Valérie Pascual, Laurent Hascoet, Jean Utke [Argonne National Lab. (Illinois, USA)], Michel Schanen [RWTH Aachen University (Germany)].

Together with colleagues in Argonne National Lab. and RWTH Aachen, we are studying how AD tools can handle MPI-parallel codes, especially in adjoint mode. Results are progressively incorporated into a library (AMPI, for Adjoinable-MPI) that is designed to provide efficient tangent and adjoint differentiation for MPI-parallel codes, independently of the AD tool used (AdolC, dco, OpenAD, TAPENADE ...). Primitives from the AMPI library dynamically orchestrate, at run-time, the MPI calls that are needed to compute the derivatives.

This year we studied issues raised by the collective reduction operations of MPI, and by the one-sided communications (i.e. remote memory access) offered by MPI-II.

The participants met on two occasions, two weeks in march in Sophia-Antipolis, and two weeks in october in Argonne.

This work was presented in particular at the meeting of the Inria-Illinois joint lab in june in Lyon. An article is in preparation.

6.2. Automatic Differentiation and Dynamic Memory

Participants: Valérie Pascual, Laurent Hascoet, Jean Utke [Argonne National Lab. (Illinois, USA)].

Adjoint differentiated code obtained by source transformation (OpenAD, TAPENADE...) consists of a forward sweep that essentially copies the original code, and a backward sweep that computes the derivatives, These two sweeps must have the same control flow shape, only reversed. The allocation and deallocation of some dynamic memory inside the forward sweep requires a similar pattern in the backward sweep. However, allocations do not always return the same memory chunk, and therefore all memory addresses must be updated to preserve their consistency in the backward sweep.

This problem can only be solved dynamically, at run-time. A compile-time analysis would have to be conservative, implying many overapproximations and in the end an unreasonably inefficient adjoint code. Our approach is thus to design a library that encapsulates all calls to memory allocation primitives (`malloc`, `free`...) in order to register the allocated addresses and to be able to restore consistency of pointers during the backward sweep. This strategy is similar to the one we use for MPI calls, cf 6.1, and is actually needed in our AMPI strategy. All we can hope from a static analysis is to detect the simple cases where addresses could be recomputed instead of stored and updated. This may apply to a significant portion of memory manipulations, and may thus reduce the overhead due to the dynamic updating.

We started developing this library, called ADMM for Adjoinable Dynamic Memory Management. TAPENADE will eventually produce adjoint code that calls these primitives instead of the standard memory management primitives.

6.3. Automatic Differentiation and iterative processes

Participants: Laurent Hascoet, Ala Taftaf.

Adjoint codes naturally propagate partial gradients backwards from the result of the simulation. However, this uses the data flow of the simulation in reverse order, at a cost that increases with the length of the simulation. AD research looks for strategies to reduce this cost, taking advantage of the structures of the given program. One such structure is iterative fixed point loops, commonplace in numerical computation. They occur at the topmost level of steady-state simulations, as well as in unsteady simulations. They may also occur deeper in the simulation, for instance in linear solvers.

It is clear that the first iterations of a fixed-point search operate on a meaningless state vector, and that reversing the corresponding data-flow is wasted effort. An adapted adjoint strategy for the iterative process should consider only the last or the few last iterations. Furthermore, there is a discrete component to an iterative algorithm, namely the number of iterations, and this makes differentiability questionable. For these reasons we are looking for a specific strategy for the adjoint, that reverses only the necessary data-flow, and that restores confidence in the validity of the derivative.

We seek inspiration in the strategies proposed by two authors [19], [27] to design one strategy that is amenable to implementation in a source-transformation AD tool such as TAPENADE. This will be triggered by user-given differentiation directives. We are also selecting example codes (a steady-state flow solver and a Newton solver) to benchmark and experiment.

Ala Taftaf presented her preliminary results at Queen Mary University in September, and at the 13th EuroAD workshop in Oxford, December 9-10. She attended a training on the CFD code OpenFOAM at Queen Mary, September 3-6.

6.4. Differentiation of third-party codes

Participants: Valérie Pascual, Laurent Hascoet, Alain Dervieux.

This year, we have differentiated two applications brought to us by academic colleagues. This is an important activity as it points us to problems that should be solved or interfaces that should be improved in TAPENADE.

- Striation simulates ionospheric plasma. It was developed in the University of Lille, then Toulouse. The Fortran90 source is relatively compact (10,000 lines). We obtained and validated the tangent and adjoint derivatives that were needed to solve an inverse problem i.e., identify the initial condition that causes an observed instability in plasma density. This work uncovered important AD issues when dynamic memory is used intensively, cf 6.2 .
- Mascaret is a hydrodynamic simulation code developed and used by EDF to study river flows. Mascaret consists of 120,000 lines of Fortran90. In this first experiment, we differentiated only one of the three kernel solvers. We obtained validated tangent and adjoint derivatives. A further collaboration with EDF and CERFACS is planned next year.

In addition, Automatic Differentiation of the CFD code AIRNUM (cf 5.1) will continue in cooperation with the partners of the FP7 project UMRIDA.

6.5. Resolution of linearised systems

Participants: Hubert Alcin [Inria Bordeaux-Sud-Ouest], Olivier Allain [Lemma], Marianna Braza [IMF-Toulouse], Alexandre Carabias, Alain Dervieux, Bruno Koobus [Université Montpellier 2], Carine Moussaed [Université Montpellier 2], Stephen Wornom [Lemma].

The work of Hubert Alcin for the ANR ECINADS on scalable parallel solvers based on coarse grids has been continued by Carine Moussaed and Bruno Koobus. This results in scalable computations up to 2048 processors.

Bruno Koobus and Carine Moussaed presented their results on “Un modèle VMS-LES dynamique pour la simulation d’écoulements autour d’obstacles” at CANUM congress, Super-Besse, France, May 21-25.

6.6. Control of approximation errors

Participants: Alexandre Carabias, Gautier Brethes, Alain Dervieux, Adrien Loseille [Gamma3 team, Inria-Rocquencourt], Frédéric Alauzet [Gamma3 team, Inria-Rocquencourt], Estelle Mbinky [Gamma3 team, Inria-Rocquencourt], Stephen Wornom [Lemma], Olivier Allain [Lemma], Anca Belme [university of Paris 6].

Third-order mesh adaptation was the main topic of the year in error control. Two PhD have been completed this year on third-order mesh adaptation:

- In team Gamma3, Estelle Mbinky has studied a method from Bernard Mourrain for transforming trilinear Taylor terms of the approximation error into a power of a bilinear term. Estelle Mbinky defended her thesis at Paris 6 on december 20.
- In our team, Alexandre Carabias (who spent most of this year with team Gamma3) has developed a 2D third-order scheme for the Euler model. The scheme is based on the ENO finite-volume formulation with quadratic reconstruction. Some effort was devoted to improve the performance of the scheme. The scheme is much less dissipative than an usual quadratic ENO scheme and of smaller cost. Implementation of a 3D version in AIRONUM (*cf* 5.1) is now starting. The 2D scheme has been the basis of an investigation of third order anisotropic mesh adaptation. Alexandre Carabias defended his thesis in Sophia-Antipolis on december 12.

A. Carabias and E. Mbinky presented their work on “A priori-based mesh adaptation for third-order accurate Euler simulation” at HONOM 2013, Bordeaux, France, March 18-22. We further studied mesh adaptation for viscous flows and we are preparing a journal article in collaboration with Gamma3 and University of Paris 6.

This year’s new topic is the combination of Multi-Grid and anisotropic mesh adaption, with the starting PhD of Gautier Brèthes. The study involves several problematics, and in particular stopping criteria and construction of correctors. This was supported by the ANR project ECINADS, ended in november, but continues with the ANR project MAIDESC (started in october, coordinated by our team) following on mesh adaption and in particular meshes for interfaces, third-order accuracy, meshes for boundary layers, and curved meshes.

TOSCA Project-Team

6. New Results

6.1. Probabilistic numerical methods, stochastic modelling and applications

Participants: Mireille Bossy, Nicolas Champagnat, Julien Claisse, Madalina Deaconu, Samuel Herrmann, James Inglis, Antoine Lejay, Sylvain Maire, Sebastian Niklitschek Soto, Denis Talay, Etienne Tanré, Denis Villemonais, Laurent Violeau.

6.1.1. Published works and preprints

- M. Bossy and J-F. Jabir (University of Valparaíso) [29], have proved the well-posedness of a conditional McKean Lagrangian stochastic model, endowed with the specular boundary condition, and further the mean no-permeability condition, in a smooth bounded confinement domain \mathcal{D} . This result extends their previous work [48], where the confinement domain was the upper-half plane. The extension of the construction to more general confinement domain exhibits difficulties that we handle by combining stochastic calculus and the analysis of kinetic equations. As a prerequisite for the study of the nonlinear case, we construct a Langevin process confined in \mathcal{D} and satisfying the specular boundary condition. We then use PDE techniques to construct the time-marginal densities of the nonlinear process from which we are able to exhibit the conditional McKean Lagrangian stochastic model.
- N. Champagnat studied in collaboration with S. Méléard (Ecole Polytechnique, Palaiseau) and P.-E. Jabin (Univ. of Maryland) adaptive dynamics and evolutionary branching in individual-based models of populations competing for resources, where resources consumption is modelled similarly as for chemostat systems of ODEs [13].
- M. Deaconu and S. Herrmann constructed a new procedure for the simulation of the hitting times of nonlinear boundaries for Bessel processes. This method, called the random walk on moving spheres algorithm, is based on two key properties: first, the explicit distribution of the first hitting time of a particular boundary for the Bessel process; second, the connexion between the Bessel process and the Euclidean norm of a Brownian motion having the same dimension. This result can be applied for the hitting time of a given level for the Cox-Ingersoll-Ross process and thus be used in models arising from finance and neurosciences [15].
- J. Inglis and E. Tanré completed their study with F. Delarue and S. Rubenthaler (Univ. Nice – Sophia Antipolis) on the global solvability of a networked system of integrate-and-fire neurons proposed in the neuroscience literature. To do this it was necessary to obtain some general estimates of the first hitting times of barriers by non-homogeneous processes, which have been collected together separately in [40], <http://hal.inria.fr/hal-00870991>.
- J. Inglis, in collaboration with O. Faugeras (EPI NEUROMATHCOMP), studied the well-posedness of stochastic neural field equations within a rigorous framework. The deterministic versions of these equations have been used to great success for the macroscopic modeling of brain activity. Their stochastic counterparts are non-trivial SPDEs, due to the presence of a nonlocal operator [26], <http://hal.inria.fr/hal-00907555>.
- A. Lejay and L. Coutin (Université de Toulouse) have continued their work on the sensitivity of the Itô's map in the context of rough paths [37].
- With L. Coutin (Université de Toulouse), A. Lejay has provided a framework for considering linear rough differential equations [49].
- With A. Kohatsu-Higa (Ritsumeikan University) and K. Yasuda (Hosei University), A. Lejay provided bounds on the weak rate of convergence of the Euler scheme when the drift term is discontinuous [41].

- S. Maire and G. Nguyen have developed a Monte Carlo method to deal with Robin and transmission conditions for elliptic diffusion equations in stratified media. It combines walk on spheres techniques and finite differences [44].
- D. Villemonais worked on the empirical distribution of Fleming-Viot type particle systems. Using couplings with reflected diffusion processes, he proved the uniform tightness of such empirical distributions and deduced the non-degeneracy of the law of diffusion processes conditioned not to hit a boundary [19].
- D. Villemonais proved in [18] a general approximation method for Markov processes conditioned not to be killed. The method is based on a mean field interacting particles system which is easy to simulate. The study also details the particular case of time/environment dependent diffusion processes.

6.1.2. Other works in progress

- N. Champagnat and B. Henry work on the long-time behaviour of the frequency spectrum for the Splitting Tree models under the infinitely-many alleles model. Specifically, they want to study the asymptotic behavior of the largest families in the “supercritical clonal” case. Such results could be applied to design statistical methods to detect positive selection of a gene in a growing population.
- N. Champagnat, D. Ritchie (ORPAILLEUR team, Inria Nancy) and B. Henry work on the design of a stochastic model for the evolution of 3D structures of proteins. Using Kpax algorithm [52], which allow to quantify the evolutionary distance between proteins, their goal is to design a statistical method to infer phylogenetic trees with particle systems methods.
- N. Champagnat and D. Villemonais obtained criterions for existence and uniqueness of quasi-stationary distributions and Q -processes for general absorbed Markov processes. A quasi-stationary distribution is a stationary distribution conditionally on non-absorption, and the Q -process is defined as the original Markov process conditioned to never be absorbed. The criterion that they obtain ensures exponential convergence of the conditioned t -marginal of the process conditioned not to be absorbed at time t , to the quasi-stationary distribution and also the exponential ergodicity of the Q -process. This work is currently being written.
- J. Claisse continued his PhD. under the supervision of N. Champagnat and D. Talay on stochastic control of population dynamics. He completed a finite-horizon optimal control problem on branching-diffusion processes. He also created and studied a hybrid model of tumor growth emphasizing the role of acidity. Key therapeutic targets appear in the model to allow investigation of optimal treatment problems.
- M. Deaconu and S. Herrmann are developing a new algorithm for the simulation of Bessel processes hitting times for non-integer dimensions. The idea is to decompose the dimension into its integer part and its fractional part and use the additivity property for squared Bessel processes. Each simulation step is splitted in two parts: one uses the integer dimension case and the other one considers hitting times of a Bessel process starting from zero.
- M. Deaconu in collaboration with L. Beznea (IMAR Bucarest) and O. Lupaşcu (Université Paris 13 and IMAR Bucarest) studies the connexion between the coagulation/fragmentation phenomena and branching processes.
- J. Inglis and D. Talay are developing a mean-field model of a network of neurons, that contains both a spatial element describing the transmission of a signal along dendrites, as well as non-homogenous weights that represent the strength of the synaptic connections. More generally, this leads to the study of the limiting behavior of non-exchangeable mean-field particle systems.
- J. Inglis and E. Tanré are continuing their collaboration with F. Delarue (Univ. Nice – Sophia Antipolis) by developing approximations to a limiting equation describing the behavior of a large network of neurons all behaving according to the integrate-and-fire model. Both a particle system approximation and an approximation involving delays are considered.
- S. Larnier and A. Lejay have worked on nearshore wave analysis and bathymetry identification through the use of a video installed on the shore [42], [43].

- A. Lejay has continued his work with R. Rebolledo (Pontificia Universidad Católica), S. Torres (Universidad de Valparaíso) and E. Mordecki (Universidad de la República) on the parametric estimation of coefficients of diffusion with discontinuous coefficients.
- S. Maire and I. Dimov (Bulgarian academy of sciences) have introduced a new Monte Carlo method to solve real or complex linear systems of equations. Coupled with sequential Monte Carlo this walk on equations method shows a very fast convergence. A similar method is in progress to solve linear integral equations.
- S. Niklitschek Soto and D. Talay have set up and solved a new martingale problem which has allowed them to get a new stochastic representation for solutions of multi-dimensional diffraction parabolic PDEs with general discontinuous coefficients. One of the main difficulties to overcome has been to identify the proper weighted local time process involved in the stochastic dynamics. This work opens the way to innovating Monte Carlo methods for this class of PDEs.
- P. Guiraud (University of Valparaíso) and E. Tanré study the effect of noise in the phenomenon of spontaneous synchronisation in a network of full connected integrate- and-fire neurons. They detail cases in which the phenomenon of synchronization persists in a noisy environment, cases in which noise permits to accelerate synchronization, and cases in which noise permits to observe synchronization while the noiseless model does not show synchronization. (Math Amsud program SIN)
- L. Capietto worked during his internship under the supervision of O. Faugeras (EPI NEUROMATH-COMP) and E. Tanré on extension of [51], in a context with several populations of homogeneous neurons. They study the limit mean field equation of the membrane potential as the number of neurons increase in a network with correlated synaptic weights.
- E. Tanré, in collaboration with O. Faugeras (EPI NEUROMATHCOMP) and the team Inference and Visual Behavior (IViBe) of Institut de Neurosciences de la Timone (INT), studied the motion of eyes, the phenomena of saccades and micro-saccades when monkeys or humans have to fix the center of a picture during a few minutes. They introduce a stochastic model to describe the typical path of the eyes on the picture and evaluate the link between the characteristics of the artificial pictures and the coefficients of the stochastic model.
- L. Violeau continued his PhD. on *Stochastic Lagrangian Models and Applications to Downscaling in Fluid Dynamics* under the supervision of M. Bossy and A. Rousseau (LEMON team, Inria Sophia Antipolis - Méditerranée). Laurent Violeau has obtained a theoretical rate of convergence of the particle approximation of kinetic conditional McKean-Vlasov stochastic models. This result is the first that explicits the complex relationship between the two sources of spacial errors in such kind of algorithm: the smoothing parameter for the conditional expectation estimator and the number of interacting particles. This theoretical convergence rate was confronted with numerical tests in the case of simplified Lagrangian models that confirm the pertinence of the theoretical bound for the error.
- C. Graham and D. Talay are writing the second volume of their series published by Springer on the Mathematical Foundations of Stochastic Simulations.
- In collaboration with N. Touzi (Ecole Polytechnique), D. Talay is studying stochastic differential equations involving local times with stochastic weights, and extensions of classical notions of viscosity solutions to PDEs whose differential operator has discontinuous coefficients and transmission boundary conditions.

6.2. Financial Mathematics

Participants: Mireille Bossy, Nicolas Champagnat, Paul Charton, Madalina Deaconu, Dalia Ibrahim, Antoine Lejay, Khaled Salhi, Denis Talay, Etienne Tanré.

6.2.1. Published works and preprints

- In collaboration with N. Maïzi (CMA - Mines Paristech) and O. Pourtallier (COPRIN team, Inria Sophia Antipolis - Méditerranée), M. Bossy studied the existence result of a Nash equilibrium between electricity producers selling their production on an electricity market and buying CO2 emission allowances on an auction carbon market. The producers' strategies integrate the coupling of the two markets via the cost functions of the electricity production. The authors set out a clear Nash equilibrium that can be used to compute equilibrium prices on both markets as well as the related electricity produced and CO2 emissions covered [30]
- In addition to the internship of K. Salhi, N. Champagnat, M. Deaconu, and A. Lejay have worked on the use of power law to predict risk in financial markets using data from Euronext NSYE stocks exchanges [33].
- P. Charton submitted an article [35] on the optimal operation of a windfarm equipped with a storage unit.

6.2.2. Other works in progress

- D. Ibrahim, D. Talay and E. Tanré worked on a model coming from technical analysis in finance. They study the Bollinger Bands indicator to detect jumps in the volatility in an extension of classical Black and Scholes models. They evaluate the efficiency of such indicators to detect the random time at which the volatility jump from a *small* value to a *large* one. A paper is being written.
- In collaboration with Victor Reutenauer and Christophe Michel (CA-CIB), D. Talay and E. Tanré worked on a model in financial mathematics including bid-ask spread cost. They study the optimal strategy to hedge an interest rate swap that pays a fixed rate against a floating rate. They present a methodology using a stochastic gradient algorithm to optimize strategies. A paper is being submitted.
- In collaboration with J. Bion-Nadal (Ecole Polytechnique and CNRS), D. Talay introduced a new calibration method based on dynamical risk measures and stochastic control PDEs. A paper is being written.

6.3. Stochastic Analysis

Participants: Nicolas Champagnat, Julien Claisse, Denis Talay.

- N. Champagnat studied in collaboration with P.-E. Jabin (Univ. of Maryland) strong existence and pathwise uniqueness for stochastic differential equations driven by a Brownian motion and with rough coefficients [34]. The method is an extension of the one of [50], which studies well-posedness for deterministic dynamical system. Strong existence and pathwise uniqueness can be proved for example if the drift vector is $L^1(W^{1,1})$ and the diffusion matrix is uniformly elliptic and $L^q(W^{1,p})$ with $2/q + d/p = 1$. This improves the previous conditions of [53].
- J. Claisse and D. Talay studied in collaboration with X. Tan (Univ. of Paris Dauphine) a conditioning argument which is often used to prove the dynamic programming principle [36]. Their study of the literature revealed that previous proofs of this argument are incorrect or incomplete. They provided a rigorous and detailed proof by setting up martingale controlled problems in a original way.

ABS Project-Team

6. New Results

6.1. Modeling Interfaces and Contacts

Docking, scoring, interfaces, protein complexes, Voronoi diagrams, arrangements of balls.

The work undertaken in this vein in 2013 will be finalized in 2014.

6.2. Modeling Macro-molecular Assemblies

Macro-molecular assembly, reconstruction by data integration, proteomics, modeling with uncertainties, curved Voronoi diagrams, topological persistence.

6.2.1. Connectivity Inference in Mass Spectrometry based Structure Determination

Participants: Frédéric Cazals, Deepesh Agarwal.

In collaboration with J. Araujo, and C. Caillouet, and D. Coudert, and S. Pérennes, from the COATI project-team (Inria-CNRS).

In [14], we consider the following MINIMUM CONNECTIVITY INFERENCE problem (MCI), which arises in structural biology: given vertex sets $V_i \subseteq V, i \in I$, find the graph $G = (V, E)$ minimizing the size of the edge set E , such that the sub-graph of G induced by each V_i is connected. This problem arises in structural biology, when one aims at finding the pairwise contacts between the proteins of a protein assembly, given the lists of proteins involved in sub-complexes. We present four contributions.

First, using a reduction of the set cover problem, we establish that MCI is APX-hard. Second, we show how to solve the problem to optimality using a mixed integer linear programming formulation (MILP). Third, we develop a greedy algorithm based on union-find data structures (Greedy), yielding a $2(\log_2 |V| + \log_2 \kappa)$ -approximation, with κ the maximum number of subsets V_i a vertex belongs to. Fourth, application-wise, we use the MILP and the greedy heuristic to solve the aforementioned connectivity inference problem in structural biology. We show that the solutions of MILP and Greedy are more parsimonious than those reported by the algorithm initially developed in biophysics, which are not qualified in terms of optimality. Since MILP outputs a set of optimal solutions, we introduce the notion of *consensus solution*. Using assemblies whose pairwise contacts are known exhaustively, we show an almost perfect agreement between the contacts predicted by our algorithms and the experimentally determined ones, especially for consensus solutions.

6.3. Algorithmic Foundations

Computational geometry, Computational topology, Voronoi diagrams, α -shapes, Morse theory.

6.3.1. Greedy Geometric Algorithms for Collection of Balls, with Applications to Geometric Approximation and Molecular Coarse-Graining

Participants: Frédéric Cazals, Tom Dreyfus.

In collaboration with S. Sachdeva (Princeton University, USA), and N. Shah (Carnegie Mellon University, USA).

Choosing balls to best approximate a 3D object is a non trivial problem. To answer it, in [18], we first address the *inner approximation* problem, which consists of approximating an object \mathcal{F}_\odot defined by a union of n balls with $k < n$ balls defining a region $\mathcal{F}_\mathcal{S} \subset \mathcal{F}_\odot$. This solution is further used to construct an *outer approximation* enclosing the initial shape, and an *interpolated approximation* sandwiched between the inner and outer approximations.

The inner approximation problem is reduced to a geometric generalization of weighted max k -cover, solved with the greedy strategy which achieves the classical $1 - 1/e$ lower bound. The outer approximation is reduced to exploiting the partition of the boundary of \mathcal{F}_Θ by the Apollonius Voronoi diagram of the balls defining the inner approximation.

Implementation-wise, we present robust software incorporating the calculation of the exact Delaunay triangulation of points with degree two algebraic coordinates, of the exact medial axis of a union of balls, and of a certified estimate of the volume of a union of balls. Application-wise, we exhibit accurate coarse-grain molecular models using a number of balls 20 times smaller than the number of atoms, a key requirement to simulate crowded cellular environments.

6.3.2. *Towards Morse Theory for Point Cloud Data*

Participants: Frédéric Cazals, Christine Roth.

In collaboration with C. Robert (IBPC / CNRS, Paris, France), and C. Mueller (ETH, Zurich).

Morse theory provides a powerful framework to study the topology of a manifold from a function defined on it, but discrete constructions have remained elusive due to the difficulty of translating smooth concepts to the discrete setting.

Consider the problem of approximating the Morse-Smale (MS) complex of a Morse function from a point cloud and an associated nearest neighbor graph (NNG). While following the constructive proof of the Morse homology theorem, we present novel concepts for critical points of any index, and the associated Morse-Smale diagram [19].

Our framework has three key advantages. First, it requires elementary data structures and operations, and is thus suitable for high-dimensional data processing. Second, it is gradient free, which makes it suitable to investigate functions whose gradient is unknown or expensive to compute. Third, in case of under-sampling and even if the exact (unknown) MS diagram is not found, the output conveys information in terms of ambiguous flow, and the Morse theoretical version of topological persistence, which consists in canceling critical points by flow reversal, applies.

On the experimental side, we present a comprehensive analysis of a large panel of bi-variate and tri-variate Morse functions whose Morse-Smale diagrams are known perfectly, and show that these diagrams are recovered perfectly.

In a broader perspective, we see our framework as a first step to study complex dynamical systems from mere samplings consisting of point clouds.

6.4. Misc

Computational Biology, Biomedicine.

6.4.1. *Book*

Participant: Frédéric Cazals.

Edited in collaboration with P. Kornprobst, from the Neuromathcomp project-team.

Biology and biomedicine currently undergo spectacular progresses due to a synergy between technological advances and inputs from physics, chemistry, mathematics, statistics and computer science. The goal of the book [15] is to evidence this synergy, by describing selected developments in the following fields: bioinformatics, biomedicine, neuroscience.

This book is unique in two respects. First, by the variety and scales of systems studied. Second, by its presentation, as each chapter presents the biological or medical context, follows up with mathematical or algorithmic developments triggered by a specific problem, and concludes with one or two success stories, namely new insights gained thanks to these methodological developments. It also highlights some unsolved and outstanding theoretical questions, with potentially high impact on these disciplines.

Two communities will be particularly interested. The first one is the vast community of applied mathematicians and computer scientists, whose interests should be captured by the added value generated by the application of advanced concepts and algorithms to challenging biological or medical problems. The second is the equally vast community of biologists. Whether scientists or engineers, they will find in this book a clear and self-contained account of concepts and techniques from mathematics and computer science, together with success stories on their favorite systems. The variety of systems described will act as an eye opener on a panoply of complementary conceptual tools. Practically, the resources listed at the end of each chapter (databases, software) will prove invaluable to get started on a specific topic.

ASCLEPIOS Project-Team

5. New Results

5.1. Medical Image Analysis

5.1.1. Segmentation of cardiac images from magnetic resonance

Participants: Jan Margeta [Correspondant], Kristin Mcleod, Antonio Criminisi [MSRC], Nicholas Ayache.

This work has been partly supported by Microsoft Research through its PhD Scholarship Programme and the European Research Council through the ERC Advanced Grant MedYMA (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Cardiac imaging, Magnetic resonance, Image segmentation, Machine learning

- We contributed our previous method to build left ventricle myocardium segmentation consensus based on the STAPLE algorithm [26]
- We enhanced our segmentation method with extra features based on the distance transform and image vesselness measures in order to segment left atria (see Fig. 1) from 3d MRI images [49]. We participated with this method in the left atrium segmentation challenge at MICCAI 2013.

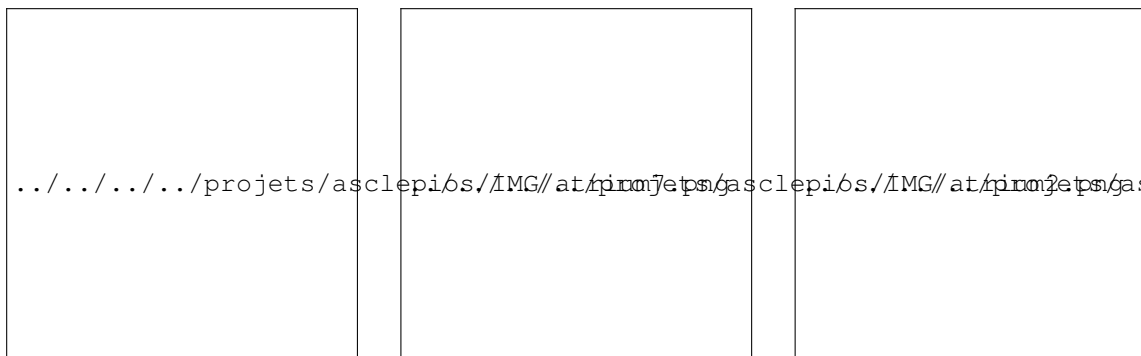


Figure 1. Segmented atria meshes from the validation dataset.

5.1.2. Brain tumor image processing and modeling

Participants: Bjoern Menze [Correspondant], Hervé Delingette, Nicholas Ayache, Nicolas Cordier, Erin Stretton, Jan Unkelbach.

We developed a new non-parametric lesion growth model for the analysis of longitudinal image sequences [59], evaluated the parametric tumor growth model of Konukoglu on longitudinal data, focusing on the relevance of DTI [40], [57], and addressed the question of how to detect tumor growth from longitudinal sequences of patients treated with angiogenesis inhibitors using registration techniques [47]. We also completed work for the 2012 MICCAI Challenge on Brain Tumor Image Segmentation (MICCAI-BRATS 2012) [79], where we also tested some of our own brain tumor image segmentation models based on random forests [42] and patch regression [38], we also participated in MICCAI-BRATS 2013 in Nagoya, Japan [67].

5.1.3. Further developing the random forest framework for medical computer vision tasks

Participants: Bjoern Menze [Correspondant], Matthias Schneider, Ezequiel Geremia, Rene Donner, Georg Langs, Gabor Szekely.

Methodological contributions include the further development of the random forest framework. We introduced the “spatially adaptive” random forest (SARF) classifier [42], and evaluated Hough regression forests for interest point detection in whole body CT image analysis, as well as for vessel detection and tracking [54]. We also evaluated alternative patch-based methods for whole body image registration [41]. As a related community effort, we organized the MICCAI-MCV workshop, also in conjunction with the MICCAI conference in Nagoya, Japan [65].

5.1.4. Statistical Analysis of Diffusion Tensor Images of the Brain

Participants: Vikash Gupta [Correspondent], Nicholas Ayache, Xavier Pennec.

Diffusion Tensor Imaging of the Brain, Tractography, Super-resolution, Statistical analysis

Diffusion tensor imaging (DTI) is gaining interest as a clinical tool for studying a number of brain diseases pertaining to white matter tracts and also as an aid in neuro-surgical planning. Unfortunately, in a clinical environment, diffusion imaging is hampered by the long acquisition times, low signal to noise ratio and a prominent partial volume effect due to thick slices. We are developing a framework for increasing the resolution of the low-resolution clinical CTI images. The method uses a maximum likelihood strategy to account for the noise and an anisotropic regularization prior to promote smoothness in homogeneous areas while respecting edges. The technique is called Higher Resolution Tensor Estimation and it uses a single clinical acquisition to produce high resolution tensor images. We aim to replace resampling techniques used for tensor normalization in population based studies, with the present method. The method itself along with quantitative results on tractography 2 were presented in MICCAI 2013 [45].

5.1.5. 3D/2D coronary arteries registration

Participants: Thomas Benseghir [Correspondant], Grégoire Malandain, Régis Vaillant [GE-Healthcare], Nicholas Ayache.

This work is done in collaboration with GE-Healthcare (Buc).

3D/2D registration; computed tomography angiography; CTA; X-ray fluoroscopy; coronary arteries

Endovascular treatment of coronary arteries involves catheter navigation through patient vasculature. Projective angiography guidance is limited in the case of chronic total occlusion where the occluded vessel can not be seen. Integrating standard preoperative CT angiography information with live fluoroscopic images addresses this limitation but requires alignment of both modalities.

We published the Iterative Closest Curve (ICC) algorithm [36] in the MICCAI 2013 conference :

- The ICC-algorithm mimics the ICP-algorithm⁶, curves being considered instead of points.
- Contrary to closest point pairing, the resulting pairings assure a topological and geometrical coherence since a curve is paired to another one (cf Figure 3).
- The developed method can deal with differences in both datasets by considering outlier rejection at the level of curve and the level of point.

5.1.6. Automatic Registration of Endoscopic Images

Participants: Anant Vemuri [Correspondant], Stéphane Nicolau [IHU Strasbourg], Luc Soler [IHU Strasbourg], Nicholas Ayache.

This work is performed in collaboration with IHU Strasbourg.

Image registration; Endoscopic imaging; Biopsy Relocalization

⁶P.J. Besl and N.D. McKay. A method for registration of 3-D shapes



Figure 2. Middle column shows a comparatively dense fiber bundle in the fornix region for the Higher Resolution Tensor Estimation method (superior-inferior view) compared to tensor resampling (left column). Right column shows a quantitative comparison of fiber lengths.



Figure 3. Left : Pairing obtained with the ICP algorithm, Middle : Pairing obtained with the ICC algorithm, Right : ICC (green) and ICP (red) registration results.

The screening of cancer lesions in the oesophagus involves obtaining biopsies at different regions along the oesophagus. The localization and tracking of these biopsy sites inter-operatively poses a significant challenge for providing targeted treatments.

Our work [61] introduces a novel framework for accurate re-positioning of the endoscope at previously targeted sites:

- it includes an electromagnetic tracking system in the loop and provides a framework for utilizing it for re-localization inter-operatively.
- We have shown on three in-vivo porcine interventions that our system can provide accurate guidance information, which was qualitatively evaluated by five experts.

5.2. Biological Image Analysis

5.2.1. Pre-clinical molecular imaging: motionless 3D image reconstruction in micro-SPECT

Participants: Marine Breuille [Correspondant, Inria], Grégoire Malandain [Inria], Nicholas Ayache [Inria], Jacques Darcourt [UNS-CAL], Philippe Franken [UNS-CAL], Thierry Pourcher [CEA].

This work is jointly conducted with the Transporter in Imagery and Oncologic Radiotherapy team (TIRO, CEA-CAL-UNSA) located in Nice.

SPECT/CT, small animal, respiratory motion, respiratory gating, 4D images, stomach, ^{99m}Tc -pertechnetate biodistribution, compartmental analysis

This work has been conducted on SPECT images acquired with a small animal device. Dynamic SPECT images provide functional information targeted by a specific radiotracer (^{99m}Tc -pertechnetate) that permit the tracking and quantifying of evolving phenomena.

- Respiratory motion induces an artificial enlargement of the moving structures (tumours, organs) in SPECT images, and biases the quantification.
- A full ad-hoc method was presented that allows the reconstruction of a single 3D SPECT image without motion artefacts [37], [6], [1].

5.2.2. Pre-clinical molecular dynamic imaging: ^{99m}Tc -pertechnetate biodistribution model of murine stomach with micro-SPECT

Participants: Marine Breuille [Correspondant, Inria], Grégoire Malandain [Inria], Nicholas Ayache [Inria], Jacques Darcourt [UNS-CAL], Philippe Franken [UNS-CAL], Thierry Pourcher [CEA].

This work is jointly conducted with the Transporter in Imagery and Oncologic Radiotherapy team (TIRO, CEA-CAL-UNSA) located in Nice.

SPECT/CT, small animal, 4D images, stomach, ^{99m}Tc -pertechnetate biodistribution, compartmental analysis

Using the coupled SPECT and CT device dedicated to small animals, functional information targeted by a specific radiotracer (^{99m}Tc -pertechnetate) can be imaged dynamically.

- ^{99m}Tc -pertechnetate is an iodide analog related to the NIS gene. Thus iodide uptake kinetics can be studied through the study of ^{99m}Tc -pertechnetate biodistribution.
- Dynamic SPECT images exhibit a progressive accumulation of ^{99m}Tc -pertechnetate in the stomach wall and diffusion in the stomach cavity.
- A first simplified model for stomach ^{99m}Tc -pertechnetate biodistribution was proposed and studied with a compartmental analysis approach using a simplified two-compartment (stomach wall and cavity) model with one input (blood) (see Figure 4) [1].
- Time activity curves of each compartment were obtained from dynamic images thanks to an original layer-based decomposition of the stomach [1].
- The first estimation of the model transfer parameters K_{ij} was performed by numerically solving the inverse problem [1].



Figure 4. Simplified two-compartment model of ^{99m}Tc -pertechnetate biodistribution in murine stomach with time-activity curves for each compartment.

5.3. Computational Anatomy

5.3.1. Longitudinal brain morphometry: statistical analysis and robust quantification of anatomical changes

Participants: Marco Lorenzi [Correspondant], Xavier Pennec, Nicholas Ayache.

Longitudinal analysis, Alzheimer's Disease, non-linear registration, brain morphometry

This project is based on the PhD thesis defended in 2012 by Marco Lorenzi, and aims at developing robust and effective instruments for the analysis of longitudinal brain changes, with special focus on the study of brain atrophy in Alzheimer's disease. The project relies on the analysis of follow-up magnetic resonance images of the brain by means of non-linear registration. During 2013 the main scientific achievements were the following:

- We developed and distributed the LCC-logDemos, an accurate and robust diffeomorphic non-linear registration algorithm [14], [16]. The algorithm implements the symmetric Local Correlation Coefficient (LCC) and is suited for both inter and intra-subject registration. The software is freely available for research purposes [here](#).
- We investigated the problem of comparing the trajectories of longitudinal morphological changes estimated in different patients. Based on our previous work on parallel transport in diffeomorphic registration, we proposed the "pole ladder" for the efficient normalization of longitudinal trajectories in a common reference space [15], [48].
- We defined an effective framework for the statistical analysis of longitudinal brain changes in clinical groups. The proposed framework enabled the characterization of abnormal morphological changes in healthy subjects at risk for Alzheimer's disease [46].
- We addressed the multi-scale analysis of longitudinal volume changes encoded by deformation fields. We provided a probabilistic framework for the consistent definition of anatomical regions of longitudinal brain atrophy across spatial scales, in order to robustly quantify regional volume changes in populations or in single patients. The framework was applied to the longitudinal analysis of group-wise atrophy in Alzheimer's disease (Figure 5), and to the tracking and quantification of treatment efficacy on brain tumors [47].

5.3.2. Longitudinal Analysis and Modeling of Brain Development during Adolescence

Participants: Mehdi Hadj-Hamou [Correspondant], Xavier Pennec, Nicholas Ayache.

This work is partly funded through the ERC Advanced Grant MedYMA 2011-291080 (on Biophysical Modeling and Analysis of Dynamic Medical Images).

Brain development, adolescence, longitudinal analysis, non-rigid registration algorithm

Due to the lack of tools to capture the subtle changes in the brain, little is known about its development during adolescence. The aim of this project is then to provide quantification and models of brain development during adolescence based on non-rigid registration of longitudinal MRIs (enabling us to capture these changes). The analysis pipeline is the following (Figure 6) :

- Register each patient's pair of images in order to get access to the longitudinal changes defined by a transformation field (parameterized by a Stationary Velocity Field).
- Transport every deformation field in a common space (template) to obtain the mean scenario and quantify the changes.
- Propose simplified models of the anatomical changes occurring during adolescence abstracting the results of the analysis.

5.3.3. Reduced-Order Statistical Models of Cardiac Growth, Motion and Blood Flow

Participants: Kristin Mcleod [Correspondant], Maxime Sermesant, Xavier Pennec.

This work was partially funded by the EU projects Care4me (ITEA2) and MD-Paedegree (FP7).



Figure 5. Group-wise scale-space analysis for the 1-year brain atrophy in 30 AD patients.



Figure 6. Pipeline for the longitudinal analysis of brain development during adolescence.

Statistical analysis, image registration, Demons algorithm, reduced models, CFD, Polyaffine, cardiac motion tracking

This work involves developing reduced models of cardiac growth, motion and blood flow, with application to the Tetralogy of Fallot heart [28].

- Extending the 2012 reduced order model of cardiac motion based on a polyaffine log-demons registration proposed at the 2012 STACOM MICCAI workshop, an additional cardiac-specific prior was added to the model to give more physiologically meaningful weight functions. Using this method, the trace of the affine matrix per region was plotted over time to establish differences between healthy subjects and asynchronous heart failure patients. The method and results were presented at the 2013 FIMH conference [52].
- Going further in analysing the affine parameters per region, statistical methods were applied to the registration parameters of the method proposed at the 2012 STACOM MICCAI workshop [50]. By applying principal component analysis to the transformation parameters stacked either column-wise or row-wise, population-based descriptors of motion in terms of the temporal or spatial components were obtained. The method was applied to 15 healthy subjects and 2 heart failure patients and presented at the 2013 MICCAI conference [51].
- The analysis of a statistical model for reduced blood flow simulations in the pulmonary artery proposed in the 2010 STACOM workshop was extended to a journal version [10], [64]. The previous work was extended to re-solve the obtained pressure and velocity bases for the subject-specific geometry by solving the Navier Stokes equations on the reduced bases. The method was applied to a data-set of 17 Tetralogy of Fallot patients.

5.3.4. Geometric Statistics

Participants: Xavier Pennec [Correspondant], Nina Miolane, Christof Seiler [Stanford], Susan Holmes [Stanford].

This work is partly funded through a France Stanford collaborative project grant (2013-2014).

Statistics, manifolds, Lie groups

The study of bi-invariant means on Lie groups [53] was further pushed by looking for the conditions of existence of bi-invariant semi-Riemannian metrics, thus relaxing the positivity constraint of Riemannian metrics [4]. This idea was based on the fact that such a bi-invariant semi-Riemannian metric exists of SE(3). Unfortunately, this does not generalize to higher dimensions. Other results on geometric statistics on regions for in the context of group-valued trees for deformation analysis were presented in [55].

5.4. Computational Physiology

5.4.1. Modeling and Simulation of Longitudinal Brain MRIs with Atrophy in Alzheimer's Disease

Participants: Bishesh Khanal [Correspondant], Nicholas Ayache, Xavier Pennec.

Alzheimer's Disease (AD), modeling atrophy, bio-physical model, simulation

We have implemented a 3D bio-physical model for the deformation of the brain with Alzheimer's Disease (AD). The model produces a deformation field of the brain when a known distribution of local volume change (atrophy) is given as the input. The obtained deformation is then used to warp the original 3D MR image. The major contribution of this work corresponds to the block "Brain Deformation" in Figure 7 .

5.4.2. Registration of time series of cardiac images

Participants: Loic Le Folgoc [Correspondant], Hervé Delingette, Antonio Criminisi, Nicholas Ayache.

This work has been partly supported by Microsoft Research through its PhD Scholarship Programme and the European Research Council through the ERC Advanced Grant MEDYMA (on Biophysical Modeling and Analysis of Dynamic Medical Images).



Figure 7. Modeling and simulation of longitudinal brain MRIs with atrophy in Alzheimer's Disease

Registration, Automatic Relevance Determination, Magnetic resonance, 3D-US

- We developed a generic approach to registration building on the framework of Automatic Relevance Determination. We applied this framework to the tracking of heart motion throughout time series of images from cine-MR, tagged-MR and 3D-US modalities.
- Our approach allows for the joint determination of model parameters, such as noise and regularization parameters, decreasing the need for manual tuning and preprocessing. Moreover, it is suitable for further analysis of uncertainty in the output of the registration.

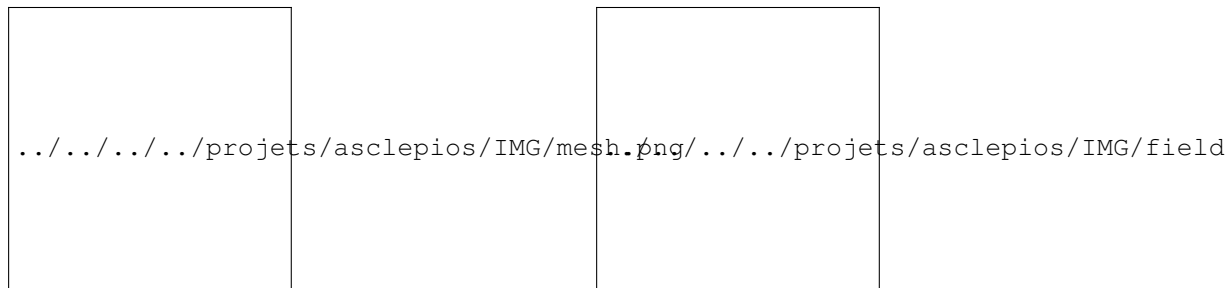


Figure 8. An instance of motion tracking on a cine MR frame. (Left) Mesh contour propagated to end systole via the registration output (Right) Computed displacement field.

5.4.3. Real-Time Cardiac Electrophysiology Computing for Training Simulator

Participants: Hugo Talbot [Correspondant], Hervé Delingette, Stephane Cotin, Maxime Sermesant, Christian Duriez.

This work was performed in collaboration with the SHACRA team in Lille.

Cardiac electrophysiology simulation, Cryoablation simulation, SOFA framework, GPU computing, patient-specific study

- Cardiac arrhythmia is a very frequent pathology that comes from abnormal electrical activity in the myocardium. This work aims at developing a training simulator for cardiologists in the context of catheterization and thermo-ablation of these arrhythmias. After tackling the issue of fast electrophysiology computation [27], a first version of our training simulator was proposed which combines virtual catheterization and interactive GPU electrophysiology modeling [70]. This year, the simulator has been improved by tackling the issue of interactive catheter navigation inside a moving venous system and a beating heart [70]. The simulator was demonstrated during the VRIPHYS 2013 workshop in Lille and the Inria-industry meeting in Paris. Personalization of the electrophysiological model using the data assimilation library Verdandi has been initiated.
- Cryotherapy simulation in collaboration with the IHU Strasbourg has been performed. This technique consists in inserting needles that freeze the surrounding tissues, thus immediately leading to cellular death of the tissues. We built a simulator able to place the cryoprobes and run a simulation representing the evolution of iceballs in living tissues [58].

5.4.4. Personalized model of the heart for cardiac therapy planning

Participants: Stéphanie Marchesseau [Correspondant], Maxime Sermesant, Hervé Delingette, Nicholas Ayache.



Figure 9. Setup of our simulator dedicated to thermo-ablation for cardiac electrophysiology.

This work is performed in the context of the PhD of Stéphanie Marchesseau in collaboration with St Thomas Hospital in London and was partially funded by ERC MedYMA.

- Personalization of the mechanical function of the heart from time series of cardiac images has been achieved by combining global calibration of a few global parameters [18] with estimation of regional contractility parameters [17] using data assimilation techniques.
- Personalized cardiac models were used to create synthetic images [22] of cardiac motion thus allowing the benchmarking of motion tracking algorithms [8], [39].

5.4.5. Cardiac Arrhythmia Radio-frequency Ablation Planning

Participants: Rocio Cabrera Lozoya [Correspondant], Maxime Sermesant, Hervé Delingette, Nicholas Ayache.

This work is performed in the context of the PhD of Rocío Cabrera Lozoya in collaboration with the CHU LIRYC Bordeaux and is funded by ERC MedYMA.

- Biophysical model development for the prediction of radio frequency ablation sites for ventricular tachycardias.
- Target site map generation for ablation therapy guidance
- Structural and functional characterization of target sites using 3D imaging and EP measurements through machine learning algorithms.
- Prediction validation with acquired clinical data

5.4.6. Computational modeling of radiofrequency ablation for the planning and guidance of abdominal tumor treatment

Participants: Chloé Audigier [Correspondant], Hervé Delingette, Tommaso Mansi, Nicholas Ayache.

This PhD is carried out jointly between the Asclepios research group, Inria Sophia Antipolis, France and the Image Analytics and Informatics global field, Siemens Corporate Research, Princeton, USA.

Radio Frequency Abation, Patient-Specific Simulation, Lattice Boltzmann Method, Computational Fluid Dynamics, Heat Transfer, Therapy Planning, Liver

- In order to obtain a computational framework for patient-specific planning of radiofrequency ablation, a patient-specific detailed anatomical model of the liver has been extracted from a standard CT image and then meshed with tetrahedra. The structures of interest include : parenchyma, lesion, hepatic vein and vena cava.
- A computational fluid dynamic model is used to estimate the patient-specific blood flow in the hepatic circulatory system. It was combined with a porous media model to compute the patient-specific blood flow distribution inside the parenchyma using the results of the CFD solver (pressures).
- Bio-heat equations and a cell death model to account for cellular necrosis have been implemented with FEM using SOFA and a Lattice Boltzmann Model to model heat propagation in biological tissues [35] leading to improved accuracy and computational efficiency.

5.4.7. Tumor growth assessment based on biophysical modeling

Participants: Erin Stretton [Correspondant], Bjoern Menze, Nicholas Ayache, Hervé Delingette.

This work was carried out during the Phd of Erin Stretton and was funded by the Care4Me project. It was performed in collaboration with Pr Mandonnet, Lariboisière hospital in Paris, and the German Cancer Research Center (DKFZ)

Glioma simulation, tumor growth.

We aim at developing image analysis methods [23] using tumor growth models in order to guide the planning of therapies (surgical removal and chemotherapy) for brain cancer (glioma) patients. Our work is focused on these objectives :

- Predicting the location of glioma recurrence after a resection surgery;
- Determining the description the of tumor cell diffusion tensor in white matter (patient-based, atlas based or isotropic) which leads to the most accurate results for predicting future tumor growth [57];
- Comparing tumor growth speeds between 8 patient cases based on biophysical modeling and various manual methods.

5.4.8. Brain tumor growth modeling : Application to radiation therapy

Participants: Matthieu Lê [Correspondant], Jan Unkelbach, Nicholas Ayache, Hervé Delingette.

This work is carried out between Asclepios research group, and the Department of Radiation Oncology of the Massachusetts General Hospital, Boston, USA. Part of this work was funded by the European Research Council through the ERC Advanced Grant MedYMA.

Glioma simulations, radiation therapy, target delineation, vasogenic edema

- We developed a tumor growth model for high grade gliomas, based on different types of cell and the vascularization of the brain.
- We studied multimodal brain tumor images to evaluate tumor infiltration.
- We used a Fisher-Kolmogorov model to improve target volume delineation for radiation therapy (see Figure 11)

5.4.9. Multimodal patch-based glioma segmentation

Participants: Nicolas Cordier [Correspondant], Bjoern Menze, Hervé Delingette, Nicholas Ayache.

Part of this work was funded by the European Research Council through the ERC Advanced Grant MedYMA (on Biophysical Modeling and Analysis of Dynamic Medical Images).

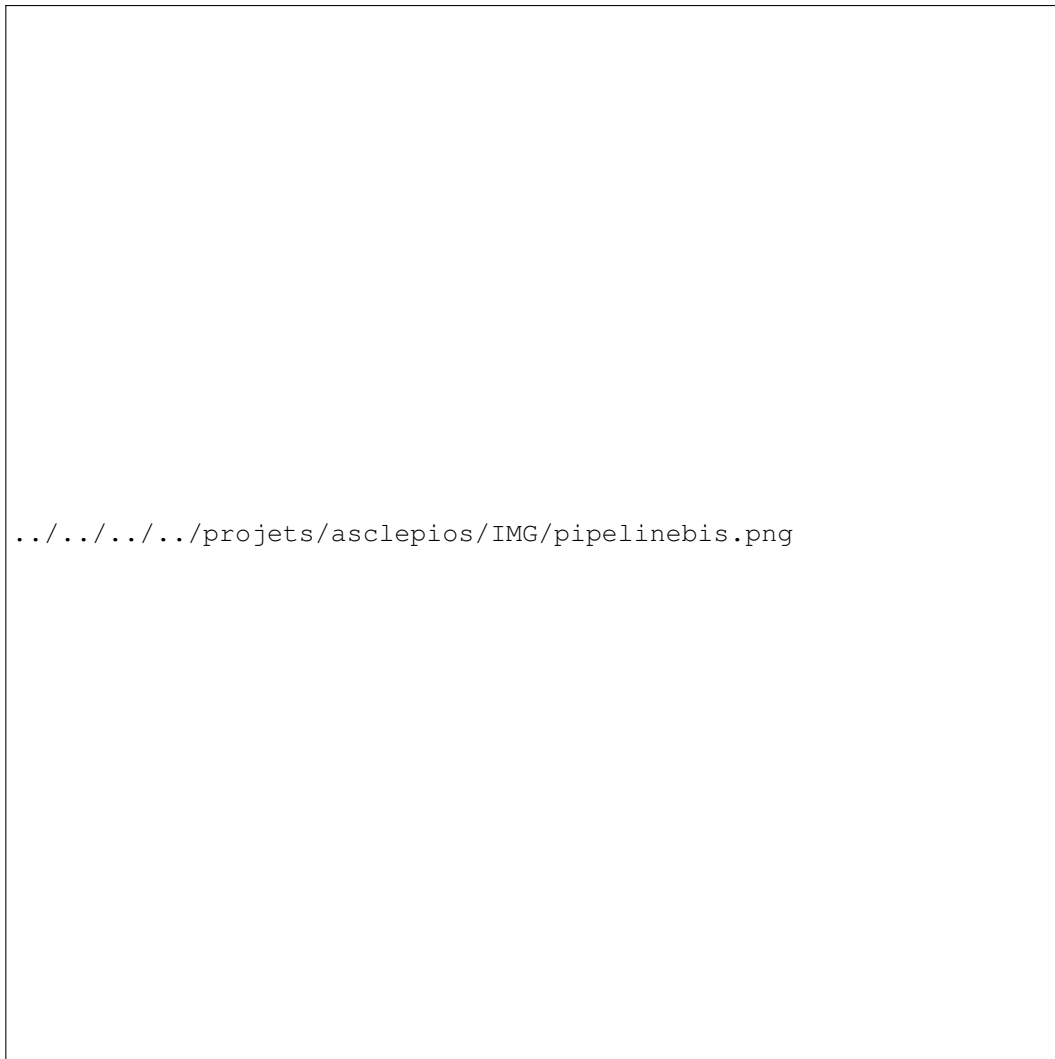


Figure 10. Steps of the proposed method (blue: input, green: processes, purple: output).

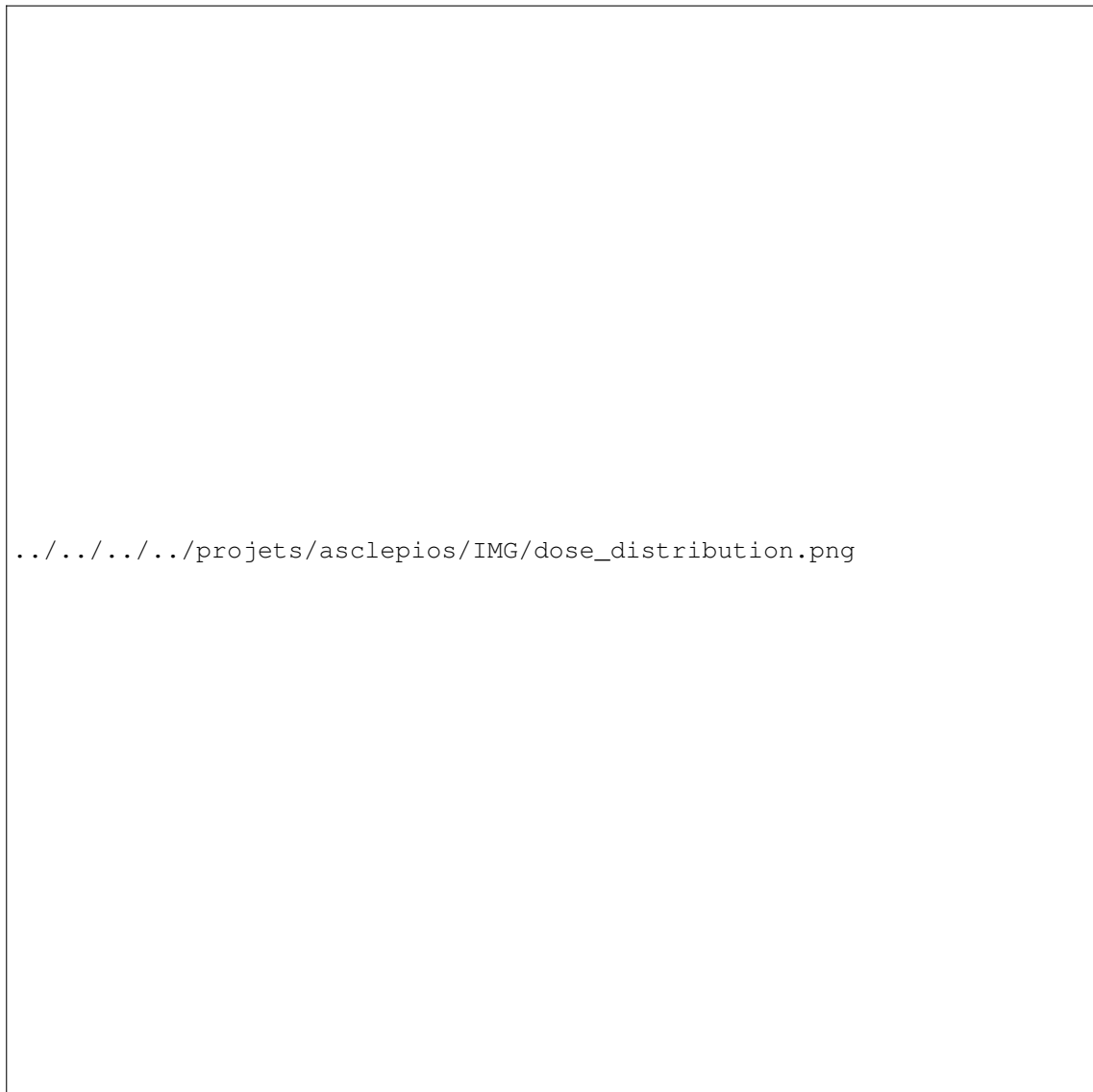


Figure 11. Comparison of the dose distribution (in Grey) clinically delivered and based on the Fisher-Kolmogorov model.

Brain, MRI, Glioma, Patch-based Segmentation, Tumor Simulation

- A patch-based approach was developed for glioma segmentation based on multi-channel 3D MRI. The method is fully automatic and does not require any learning step.
- Features: multi-channel MR intensities in local neighborhoods.
- A heuristic label fusion strategy was introduced and showed promising results, as shown in Figure 12 .
- The algorithm was ranked 5th in the Brain Tumor Segmentation Challenge (BraTS) at MICCAI 2013 [67].
- Large unlabeled glioma MRI databases are being incorporated in the framework.



Figure 12. Real high-grade case. From left to right: Vote maps for background, necrosis and non-enhancing tumor (merged), edema, enhancing tumor; Segmentation map. From top to bottom: saggital, axial, and coronal views.

ATHENA Project-Team

6. New Results

6.1. Improving Diffusion MRI Signal and Acquisition

6.1.1. Design of multishell sampling schemes with uniform coverage in diffusion MRI

Participants: Emmanuel Caruyer [SBIA, University of Pennsylvania Medical School,USA], Christophe Lenglet [CMRR, Department of Radiology, University of Minnesota,USA], Guillermo Sapiro [Electrical & Computer Engineering Dept, Duke University,USA], Rachid Deriche.

In diffusion MRI, a technique known as diffusion spectrum imaging reconstructs the propagator with a discrete Fourier transform, from a Cartesian sampling of the diffusion signal. Alternatively, it is possible to directly reconstruct the orientation distribution function in q-ball imaging, providing so-called high angular resolution diffusion imaging. In between these two techniques, acquisitions on several spheres in q-space offer an interesting trade-off between the angular resolution and the radial information gathered in diffusion MRI. A careful design is central in the success of multishell acquisition and reconstruction techniques.

The design of acquisition in multishell is still an open and active field of research, however. In this work, we provide a general method to design multishell acquisition with uniform angular coverage. This method is based on a generalization of electrostatic repulsion to multishell.

The impact of our method on the angular resolution in one and two bundles of fiber configurations is evaluated using simulations. Compared to more commonly used radial sampling, we show that our method improves the angular resolution, as well as fiber crossing discrimination.

This work has been published in [14].

6.1.2. Motion detection in diffusion MRI via online ODF estimation

Participants: Emmanuel Caruyer [SBIA, University of Pennsylvania Medical School,USA], Iman Aganj [Martinos Center for Biomedical Imaging, MGH, Harvard Medical School,USA], Christophe Lenglet [CMRR, Department of Radiology, University of Minnesota,USA], Guillermo Sapiro [Electrical & Computer Engineering Dept, Duke University,USA], Rachid Deriche.

The acquisition of high angular resolution diffusion MRI is particularly long and subject motion can become an issue. The orientation distribution function (ODF) can be reconstructed online incrementally from diffusion-weighted MRI with a Kalman filtering framework. This online reconstruction provides real-time feedback throughout the acquisition process. In this work, the Kalman filter is first adapted to the reconstruction of the ODF in constant solid angle. Then, a method called STAR (STatistical Analysis of Residuals) is presented and applied to the online detection of motion in high angular resolution diffusion images. Compared to existing techniques, this method is image based and is built on top of a Kalman filter. Therefore, it introduces no additional scan time and does not require additional hardware. The performance of STAR is tested on simulated and real data and compared to the classical generalized likelihood ratio test. Successful detection of small motion is reported (rotation under 2 degrees) with no delay and robustness to noise.

This work has been published in [13].

6.1.3. A Robust variational approach for simultaneous smoothing and estimation of DTI

Participants: Rachid Deriche, Meizhu Liu [Department of CISE, University of Florida, Gainesville, USA], Baba C. Vemuri [Department of CISE, University of Florida, Gainesville, USA].

Estimating diffusion tensors is an essential step in many applications — such as diffusion tensor image (DTI) registration, segmentation and fiber tractography. Most of the methods proposed in the literature for this task are not simultaneously statistically robust and feature preserving techniques. In this work, we propose a novel and robust variational framework for simultaneous smoothing and estimation of diffusion tensors from diffusion MRI. Our variational principle makes use of a recently introduced total Kullback–Leibler (tKL) divergence for DTI regularization. tKL is a statistically robust dissimilarity measure for diffusion tensors, and regularization by using tKL ensures the symmetric positive definiteness of tensors automatically. Further, the regularization is weighted by a non-local factor adapted from the conventional non-local means filters. Finally, for the data fidelity, we use the nonlinear least-squares term derived from the Stejskal–Tanner model. We present experimental results depicting the positive performance of our method in comparison to competing methods on synthetic and real data examples.

This work has been published in [20].

6.1.4. *Tensor estimation and visualization using dMRI*

Participants: Dalila Cherif [University of Boumerdes, Algeria], Ali Chellouche [University of Boumerdes, Algeria], Amazigh Ait-Ouakli [University of Boumerdes, Algeria], Youcef Benamara [University of Boumerdes, Algeria], Rachid Deriche.

Diffusion tensor imaging in a non-invasive in vivo image modality that allows us to measure molecular diffusion of water in tissues. We characterize diffusion transport of water by an effective diffusion tensor D . The practical importance of the effective diffusion tensor is that it contains new and useful structural and physiological informations about tissues that were previously unobtainable. In this work, we present a software implementation of the estimation of these tensors and their visualization in order to extract these informations.

This work has been published in [28]

6.2. Modeling in Diffusion MRI

6.2.1. *A computational diffusion MRI and parametric dictionary learning framework for modeling the diffusion signal and its features*

Participants: Sylvain Merlet, Emmanuel Caruyer [SBIA, University of Pennsylvania Medical School, USA], Aurobrata Ghosh, Rachid Deriche.

In this work, we first propose an original and efficient computational framework to model continuous diffusion MRI (dMRI) signals and analytically recover important diffusion features such as the Ensemble Average Propagator (EAP) and the Orientation Distribution Function (ODF). Then, we develop an efficient parametric dictionary learning algorithm and exploit the sparse property of a well-designed dictionary to recover the diffusion signal and its features with a reduced number of measurements. The properties and potentials of the technique are demonstrated using various simulations on synthetic data and on human brain data acquired from 7T and 3T scanners. It is shown that the technique can clearly recover the dMRI signal and its features with a much better accuracy compared to state-of-the-art approaches, even with a small and reduced number of measurements. In particular, we can accurately recover the ODF in regions of multiple fiber crossing, which could open new perspectives for some dMRI applications such as fiber tractography.

This work has been published in Medical Image Analysis [21]. It is part of Merlet's PhD thesis defended on Sept. 11th, 2013 [11].

6.2.2. *Continuous diffusion signal, EAP and ODF estimation via compressive sensing in diffusion MRI*

Participants: Sylvain Merlet, Rachid Deriche.

In this work, we exploit the ability of Compressed Sensing (CS) to recover the whole 3D Diffusion MRI (dMRI) signal from a limited number of samples while efficiently recovering important diffusion features such as the Ensemble Average Propagator (EAP) and the Orientation Distribution Function (ODF). Some attempts to use CS in estimating diffusion signals have been done recently. However, this was mainly an experimental insight of CS capabilities in dMRI and the CS theory has not been fully exploited. In this work, we also propose to study the impact of the sparsity, the incoherence and the RIP property on the reconstruction of diffusion signals. We show that an efficient use of the CS theory enables to drastically reduce the number of measurements commonly used in dMRI acquisitions. Only 20–30 measurements, optimally spread on several b-value shells, are shown to be necessary, which is less than previous attempts to recover the diffusion signal using CS. This opens an attractive perspective to measure the diffusion signals in white matter within a reduced acquisition time and shows that CS holds great promise and opens new and exciting perspectives in diffusion MRI (dMRI).

This work has been published in *Medical Image Analysis* [22]. It is part of Merlet's PhD thesis defended on Sept. 11th, 2013 [11].

6.2.3. *Constrained diffusion kurtosis imaging using ternary quartics & MLE*

Participants: Aurobrata Ghosh, Tristan Milne, Rachid Deriche.

Diffusion kurtosis imaging (DKI) is a recent improvement over diffusion tensor imaging that characterizes tissue by quantifying non-gaussian diffusion using a 3D fourth-order kurtosis tensor. DKI needs to consider three constraints to be physically relevant. Further, it can be improved by considering the Rician signal noise model. A DKI estimation method is proposed that considers all three constraints correctly, accounts for the signal noise and incorporates efficient gradient-based optimization to improve over existing methods.

In this work, the ternary quartic parameterization is utilized to elegantly impose the positivity of the kurtosis tensor implicitly. Sequential quadratic programming with analytical gradients is employed to solve nonlinear constrained optimization efficiently. Finally, a maximum likelihood estimator based on Rician distribution is considered to account for signal noise.

Extensive experiments conducted on synthetic data verify a MATLAB implementation by showing dramatically improved performance in terms of estimation time and quality. Experiments on in vivo cerebral data confirm that in practice the proposed method can obtain improved results.

This work has been published in [18].

6.2.4. *Compressive Sensing DSI*

Participants: Sylvain Merlet, Michael Paquette [Sherbrooke Connectivity Imaging Laboratory, Computer Science Department, Université de Sherbrooke, Québec, Canada], Maxime Descoteaux [Sherbrooke Connectivity Imaging Laboratory, Computer Science Department, Université de Sherbrooke, Québec, Canada], Rachid Deriche.

Compressive Sensing (CS) offers an efficient way to decrease the number of measurements required in Diffusion Spectrum Imaging (DSI). This method aims to reconstruct the Ensemble Average Propagator (EAP) and, for the purpose of this contest, we compute the numerical Orientation Distribution Function (ODF) by integrating the EAP over a solid angle. In this abstract, we briefly describe three important points underlying the CS technique in order to accelerate DSI, namely the sparsity, the Restricted Isometry Property (RIP) and the L1 reconstruction scheme. Due to the high b-values required in the sampling protocol, our approach enters the heavyweight sampling category. Nevertheless, only 64 measurements are used for the reconstruction.

This work has been published in [31]. It is part of Merlet's PhD thesis defended on Sept. 11th, 2013 [11].

6.2.5. *4th Order symmetric tensors and positive ADC modelling*

Participants: Aurobrata Ghosh, Rachid Deriche.

High Order Cartesian Tensors (HOTs) were introduced in Generalized DTI (GDTI) to overcome the limitations of DTI. HOTs can model the apparent diffusion coefficient (ADC) with greater accuracy than DTI in regions with fiber heterogeneity. Although GDTI HOTs were designed to model positive diffusion, the straightforward least square (LS) estimation of HOTs doesn't guarantee positivity. In this work, we address the problem of estimating 4th order tensors with positive diffusion profiles. Two known methods exist that broach this problem, namely a Riemannian approach based on the algebra of 4th order tensors, and a polynomial approach based on Hilbert's theorem on non-negative ternary quartics. In this work, we review the technicalities of these two approaches, compare them theoretically to show their pros and cons, and compare them against the Euclidean LS estimation on synthetic, phantom and real data to motivate the relevance of the positive diffusion profile constraint.

This work has been published in [37].

6.2.6. Higher-Order tensors in diffusion imaging: A survey

Participants: Thomas Schultz [MPI for Intelligent Systems, Tubingen, Germany], Andrea Fuster [Eindhoven University of Technology, The Netherlands], Aurobrata Ghosh, Luc Florack [Eindhoven University of Technology, The Netherlands], Rachid Deriche, Lek-Heng Lim [University of Chicago, USA].

Diffusion imaging is a noninvasive tool for probing the microstructure of fibrous nerve and muscle tissue. Higher-order tensors provide a powerful mathematical language to model and analyze the large and complex data that is generated by its modern variants such as High Angular Resolution Diffusion Imaging (HARDI) or Diffusional Kurtosis Imaging. This survey gives a careful introduction to the foundations of higher-order tensor algebra, and explains how some concepts from linear algebra generalize to the higher-order case. From the application side, it reviews a variety of distinct higher-order tensor models that arise in the context of diffusion imaging, such as higher-order diffusion tensors, q-ball or fiber Orientation Distribution Functions (ODFs), and fourth-order covariance and kurtosis tensors. By bridging the gap between mathematical foundations and application, it provides an introduction that is suitable for practitioners and applied mathematicians alike, and propels the field by stimulating further exchange between the two.

This work has been published in [39].

6.2.7. Regularized spherical polar fourier diffusion MRI with optimal dictionary learning

Participants: Jian Cheng [University of North Carolina at Chapel Hill,USA], Tianzi Jiang [LIAMA, China], Rachid Deriche, Shen Dinggang [University of North Carolina at Chapel Hill,USA], Yap Pew-Thian [University of North Carolina at Chapel Hill,USA].

One important problem in diffusion MRI (dMRI) is to recover the diffusion weighted signal from only a limited number of samples in q-space. An ideal framework for solving this problem is Compressed Sensing (CS), which takes advantage of the signal's sparseness or compressibility, allowing the entire signal to be reconstructed from relatively few measurements. CS theory requires a suitable dictionary that sparsely represents the signal. To date in dMRI there are two kinds of Dictionary Learning (DL) methods: 1) discrete representation based DL (DR-DL), and 2) continuous representation based DL (CR-DL). Due to the discretization in q-space, DR-DL suffers from the numerical errors in interpolation and regridding. By considering a continuous representation using Spherical Polar Fourier (SPF) basis, this work proposes a novel CR-DL based Spherical Polar Fourier Imaging, called DL-SPFI, to recover the diffusion signal as well as the Ensemble Average Propagator (EAP) in continuous 3D space with closed form. DL-SPFI learns an optimal dictionary from the space of Gaussian diffusion signals. Then the learned dictionary is adaptively applied for different voxels in a weighted LASSO framework to robustly recover the diffusion signal and the EAP. Compared with the start-of-the-art CR-DL method by Merlet et al. and DRDL by Bilgic et al., DL-SPFI has several advantages. First, the learned dictionary, which is proved to be optimal in the space of Gaussian diffusion signal, can be applied adaptively for different voxels. To our knowledge, this is the first work to learn a voxel-adaptive dictionary. The importance of this will be shown theoretically and empirically in the context of EAP estimation. Second, based on the theoretical analysis of SPF basis, we devise an efficient learning process in a small subspace of SPF coefficients, not directly in q-space as done by Merlet et al.. Third, DL-SPFI also devises different regularization for different atoms in the learned dictionary for robust estimation,

by considering the structural prior in the space of signal exemplars. We evaluate DL-SPFI in comparison to L1-norm regularized SPFI (L1-SPFI) with fixed SPF basis, and the DR-DL by Bilgic et al. The experiments on synthetic data and real data demonstrate that the learned dictionary is sparser than SPF basis and yields lower reconstruction error than Bilgic's method, even though only simple synthetic Gaussian signals were used for training in DL-SPFI in contrast to real data used by Bilgic et al.

This work has been published in [27].

6.2.8. *Fiber orientation distribution from non-negative sparse recovery*

Participants: Aurobrata Ghosh, Thinhinane Megherbi [USTHB, Algeria], Linda Oulebsir-Boumghar [USTHB, Algeria], Rachid Deriche.

We revisit the theory of spherical deconvolution and propose a new fiber orientation distribution (FOD) model that can efficiently reconstruct extremely narrow fiber-crossings from limited number of acquisitions. First, we show how to physically model fiber-orientations as rank-1 tensors. Then, we parameterize the FODs with tensors that are decomposable into non-negative sums of rank-1 tensors and finally, we propose a non-negative sparse recovery scheme to estimate FODs of any tensor order from limited acquisitions. Our method features three important advantages: (1) it estimates non-negative FODs, (2) it estimates the number of fiber-compartments, which need not be predefined and (3) it computes the fiber-directions directly, rendering maxima detection superfluous. We test for various SNRs on synthetic, phantom and real data and find our method accurate and robust to signal-noise: fibers crossing up to 23° are recovered from just 21 acquisitions. This opens new and exciting perspectives in diffusion MRI (dMRI), where our improved characterization of the FOD can be of great help for applications such as tractography.

This work has been published in [29].

6.2.9. *A polynomial approach for extracting the extrema of a spherical function and its application in diffusion MRI*

Participants: Aurobrata Ghosh, Elias Tsigaridas [PolSys Project-Team, Inria, Paris Rocquencourt, France], Bernard Mourrain [Galaad Project-Team, Inria, Sophia Antipolis, Méditerranée, France], Rachid Deriche.

This work has been partially supported by the ANR project NucleiPark and the France-Parkinson Association.

Antipodally symmetric spherical functions play a pivotal role in diffusion MRI in representing sub-voxel-resolution microstructural information of the underlying tissue. This information is described by the geometry of the spherical function. In this work we propose a method to automatically compute all the extrema of a spherical function. We then classify the extrema as maxima, minima and saddle-points to identify the maxima. We take advantage of the fact that a spherical function can be described equivalently in the spherical harmonic (SH) basis, in the symmetric tensor (ST) basis constrained to the sphere, and in the homogeneous polynomial (HP) basis constrained to the sphere. We extract the extrema of the spherical function by computing the stationary points of its constrained HP representation. Instead of using traditional optimization approaches, which are inherently local and require exhaustive search or re-initializations to locate multiple extrema, we use a novel polynomial system solver which analytically brackets all the extrema and refines them numerically, thus missing none and achieving high precision.

To illustrate our approach we consider the Orientation Distribution Function (ODF). In diffusion MRI the ODF is a spherical function which represents a state-of-the-art reconstruction algorithm whose maxima are aligned with the dominant fiber bundles. It is, therefore, vital to correctly compute these maxima to detect the fiber bundle directions. To demonstrate the potential of the proposed polynomial approach we compute the extrema of the ODF to extract all its maxima. This polynomial approach is, however, not dependent on the ODF and the framework presented in this work can be applied to any spherical function described in either the SH basis, ST basis or the HP basis.

This work has been published in [19].

6.2.10. ODF maxima computation using hill climbing algorithm

Participants: Thinhinane Megherbi [USTHB, Algeria], Makhlof Laouchedi [EMP, Algeria], Houssein Khabatti [EMP, Algeria], Linda Oulebsir-Boumghar [USTHB, Algeria], Ishak Serrat [EMP, Algeria], Vincent Perlberg [LIF, UMRS 678, INSERM, UPMC - Paris 6], Rachid Deriche.

Diffusion MRI (dMRI) is the only technique to probe in-vivo and non-invasively fiber structure of white matter. Diffusion was first modeled using the classical Second Order Diffusion Tensor model. However, this model is limited in regions of multiple fiber crossings and this has motivated the development of many approaches to extract crossing fibers. Methods like Diffusion Spectrum Imaging (DSI), High Angular Resolution Diffusion Imaging (HARDI) and the High Order Tensor techniques have been proposed to reconstruct specific functions like the Orientation Distribution Function (ODF) whose maxima do correspond to the directions of the multiple fibers.

In this work, we are interested to extract all the crossing fibers characterized as the maxima of the Orientation Distribution Function (ODF). A Hill Climbing algorithm based approach has been developed and implemented to efficiently and accurately extract all the fibers. Promising experimental results obtained with synthetic and real data illustrate the potential of the technique.

This work has been submitted to ISBI'2014 and accepted for presentation and publication.

6.2.11. On SHORE and SPF bases

Participants: Elodie Pozzi, Gonzalo Sanguinetti, Rachid Deriche.

The 3D Simple Harmonic Oscillation Reconstruction and Estimation (SHORE) basis and the Spherical Polar Fourier (SPF) basis were introduced recently to represent the dMRI signal in the full 3D Q-space. SPF presents some continuity problems at the origin which led to our development of the modified SPF basis we introduced to overcome this issue. These bases can be written with radial and angular functions. The radial part of the decomposition is a family of orthogonal functions (the Gauss-Laguerre functions) and the angular component are the spherical harmonic functions. Even though they look similar, they have different properties. The first objective of this work has been to analyse and clarify the differences between those bases. This has been accomplished by describing the spanned spaces. The second goal has been to classify the bases according to their continuity and differentiability and thus draw a more focused comparison between.

This on-going work will be submitted to a journal.

6.3. From DW-MRI to Fiber Pathways and Microstructures Recovery

6.3.1. Mapping Average axon diameters under long diffusion time

Participants: Gonzalo Sanguinetti, Rachid Deriche.

This work proposes an original method to recover axon diameter distribution (ADD) parameters using nuclear magnetic resonance. White matter (WM) is modelled as a bi-compartmental medium composed of an intra axonal space where the diffusion is restricted and an extra axonal space where diffusion is hindered. Under the assumption of long diffusion time, we provide a novel and efficient model for the component of the signal due to the restricted part. This technique might be interpreted as an interesting simplification of the AxCaliber framework, which leads to a simpler model and an extremely faster acquisition protocol. To test and validate our method, we use the open-source toolkit Camino for computing Monte-Carlo simulations of NMR data and model the WM as 3D cubic environments, formed by parallel cylinders with gamma distributed radii. Promising experimental results illustrate the potential of the proposed method.

This work has been submitted to ISBI'2014 and accepted for presentation and publication.

6.3.2. NMR characterization of cylinder radii distribution using a SHORE-based regularization method.

Participants: Gonzalo Sanguinetti, Daniel Alexander [Centre for Medical Image Computing, Dept. Computer Science, UCL], Matt Hall [Centre for Medical Image Computing, Dept. Computer Science, UCL], Rachid Deriche.

In this work, we extend the framework presented by Ozarslan et al [79] by adding a regularization term for better measuring the moments of a cylinder radii distribution by means of NMR acquisitions. The added value of the regularization term is tested and validated using Monte Carlo simulations of NMR signals from complex white matter-like environment. The open source toolkit CAMINO [50] is used for computing the simulations and an excellent agreement is obtained between the ground truth and the estimated moments.

This work has been submitted to ISMRM'2014.

6.3.3. *Quantitative comparison of reconstruction methods for intra-voxel fiber recovery from diffusion MRI*

Participants: Emmanuel Caruyer [SBIA, University of Pennsylvania Medical School, USA], Sylvain Merlet, Rachid Deriche.

In diffusion MRI, a technique known as diffusion spectrum imaging reconstructs the propagator with a discrete Fourier transform, from a Cartesian sampling of the diffusion signal. Alternatively, it is possible to directly reconstruct the orientation distribution function in q-ball imaging, providing so-called high angular resolution diffusion imaging. In between these two techniques, acquisitions on several spheres in q-space offer an interesting trade-off between the angular resolution and the radial information gathered in diffusion MRI. A careful design is central in the success of multishell acquisition and reconstruction techniques and the design of acquisition in multishell is still an open and active field of research.

In this work, we propose a novel method to design sampling schemes with optimal angular coverage and show the positive impact on angular resolution in diffusion MRI. Our method is based on a generalization of electrostatic repulsion to multishell and allows to design multishell acquisition with uniform angular coverage.

We evaluated the impact of our method using simulations, on the angular resolution in one and two bundles of fiber configurations. Compared to more commonly used radial sampling, we show that our method improves the angular resolution, as well as fiber crossing discrimination.

This work has been published in [16].

6.3.4. *Choosing tractography parameters to improve connectivity mapping*

Participants: Gabriel Girard [SCIL Lab., Sherbrooke University], Kevin Whittingstall [SCIL Lab., Sherbrooke University], Kevin Whittingstall [SCIL Lab., Sherbrooke University], Rachid Deriche.

Diffusion-weighted imaging (DWI) is often used as a starting point for in vivo white matter (WM) connectivity to reconstruct potential WM pathways between brain areas. Tractography algorithms have many parameters which can influence reconstruction and connectivity. Various choices of parameters have been proposed. But how does one choose the best set of parameters? In this study, we varied three critical parameters while monitoring connectivity score using the Tractometer evaluation system on the International Symposium on Biomedical Imaging (ISBI) Challenge synthetic dataset. The three parameters were: The maximum deviation angle between two consecutive tractography steps (this addresses the hypothesis of smoothness of the WM pathways), the spherical function (SF) threshold (this aims at removing noisy propagation directions during the tractography process) and the initial SF threshold (this aims at removing initial noise at the seeds and to start tractography in a good tangent direction to the WM bundle).

This work has been submitted to ISMRM'2014.

6.3.5. *Improved tractography using structural priors*

Participants: Gabriel Girard [SCIL Lab., Sherbrooke University], Maxime Descoteaux [SCIL Lab., Sherbrooke University], Kevin Whittingstall [SCIL Lab., Sherbrooke University], Rachid Deriche.

In this work, we propose better tractography parameters in term of global connectivity and a novel tractography stopping criterion based on partial volume estimation maps, calculated from a T1-weighted image. We also propose a particle filtering method using anatomical information as prior for tractography to enforce streamlines connecting gray matter regions and reducing the proportion of erroneous streamlines. Results show streamlines more uniformly distributed among long and short, and small and large white matter bundles. This provides connectivity estimation not underestimated for bundles having higher complexity. Quantitative analysis is done on synthetic datasets and qualitative results are shown on real data. The proposed method takes advantage of prior information on the brain to change the dMRI-based tracking direction and help providing streamlines that can quantify the brain structure.

This on-going work will be submitted to NeuroImage.

6.3.6. *From diffusion MRI to brain connectomics*

Participants: Aurobrata Ghosh, Rachid Deriche.

Diffusion MRI (dMRI) is a unique modality of MRI which allows one to indirectly examine the microstructure and integrity of the cerebral white matter in vivo and non-invasively. Its success lies in its capacity to reconstruct the axonal connectivity of the neurons, albeit at a coarser resolution, without having to operate on the patient, which can cause radical alterations to the patient's cognition. Thus dMRI is beginning to assume a central role in studying and diagnosing important pathologies of the cerebral white matter, such as Alzheimer's and Parkinson's diseases, as well as in studying its physical structure in vivo. In this work, we present an overview of the mathematical tools that form the framework of dMRI – from modelling the MRI signal and measuring diffusion properties, to reconstructing the axonal connectivity of the cerebral white matter, i.e., from Diffusion Weighted Images (DWIs) to the human connectome.

This work has been published in [38].

6.4. Forward and Inverse Problems in MEEG

6.4.1. *Source localization using rational approximation on plane sections*

Participants: Maureen Clerc [Athena Project-Team, Inria, Sophia Antipolis, Méditerranée, France], Théodore Papadopoulo [Athena Project-Team, Inria, Sophia Antipolis, Méditerranée, France], Juliette Leblond [Apics Project-Team, Inria, Sophia Antipolis, Méditerranée, France], Jean-Paul Marmorat [CMA, Ecole des Mines Paristech, Sophia Antipolis, France].

In functional neuroimaging, a crucial problem is to localize active sources within the brain non-invasively, from knowledge of electromagnetic measurements outside the head. Identification of point sources from boundary measurements is an ill-posed inverse problem. In the case of electroencephalography (EEG), measurements are only available at electrode positions, the number of sources is not known in advance and the medium within the head is inhomogeneous. We have presented [49] a new method for EEG source localization, based on rational approximation techniques in the complex plane. The method is used in the context of a nested sphere head model, in combination with a cortical mapping procedure. Results on simulated data prove the applicability of the method in the context of realistic measurement configurations. In the continuation of this work, we are in discussion with an industrial partner (BESA, Munich) for a scientific partnership.

6.4.2. *Dictionary learning for multitrial datasets*

Participants: Maureen Clerc, Sebastian Hitziger, Théodore Papadopoulo.

Following the path opened with the Consensus matching Pursuit method (CMP) [46], we continue our endeavour to avoid signal averaging using directly the raw signal with the assumption that events of interest are those that repeat in each trial [36]. Towards such a goal, and to improve the simple dictionary used in CMP, we have adapted dictionary learning methods to multitrial bio-electric signals, by explicitly implementing jitter invariance [30]. This allows for a much more detailed data-driven description of events. For example, using local field potential signals of chemically induced spikes (in a rat model), we have been able to distinguish several spike shapes which show some coherence in time. The method has been recently extended to detect spike events in continuous signals (i.e. not organized in epochs). While it requires a good signal to noise ratio, the method is very general and has also been used for various other signal types (see section 6.5).

6.5. Coupling functional and structural models

6.5.1. *Cortex parcellation via diffusion data as prior knowledge for the MEG inverse problem*

Participants: Anne-Charlotte Philippe, Maureen Clerc, Théodore Papadopoulo, Rachid Deriche.

In this work, a new approach is presented for the recovery of dipole magnitudes in a distributed source model for magnetoencephalographic (MEG) imaging. This method consists in introducing prior knowledge regarding the anatomical connectivity in the brain to this ill-posed inverse problem. Towards this goal, a cortex parcellation is performed using structural information coming from diffusion MRI (dMRI), the only non-invasive modality allowing to have access to the structure of the WM tissues. Then, sources in the same diffusion parcel are constrained, in the MEG inverse problem, to have close magnitude values. Results of our method on MEG simulations are presented and favorably compared with classical source reconstruction methods.

This work has been published in [32], and is part of A.C. Philippe's Ph.D thesis [12].

6.5.2. *Diffusion-Weighted Imaging tractography-based parcellation of the human cortex as regularization term for the MEG inverse problem*

Participants: Anne-Charlotte Philippe, Maureen Clerc, Théodore Papadopoulo, Rachid Deriche.

The purpose of this work is to advocate the use of structural connectivity information to regularize the ill-posed MEG inverse problem. Diffusion MRI being the only non invasive modality allowing to have access to the connectivity profile of cortical sources, the proposed method called Diff-MNE consists in the introduction of a cortex parcellation based on diffusion data regularization term to the MEG inverse problem. Our method is tested on synthetic and real human brain data and compared to the classical minimum-norm method. Results show that a diffusion-based cortex parcellation as a regularization term for the MEG inversion process improves the source reconstruction. This proves the interest of merging diffusion MRI and MEG data.

This work is under submission to a Neuroimage and is part of A.C. Philippe's Ph.D thesis [12]

6.5.3. *Propagation of epileptic spikes revealed by diffusion-based constrained MEG source reconstruction*

Participants: Anne-Charlotte Philippe, Maureen Clerc, Théodore Papadopoulo, Rachid Deriche.

In this work, we study the propagation of an epileptic spike (from single event data). As in the two previous sections, a cortex parcellation is performed using structural information coming from diffusion MRI. Then, a MEG inverse problem is defined on a parcellated source space which imposes constant activity on each parcel. This inverse problem is applied separately for measurements obtained in a given time range. The most active parcels over the time range are located and their time course are displayed. This allowed the study of the propagation of an epileptic spike via those active parcels. Results on real data shows varying spatial propagations of an epileptic spike for the same subject.

This work has been published in [40], and is part of A.C. Philippe's Ph.D thesis [12].

6.6. Brain Computer Interfaces

6.6.1. *Combining ERD and ERS features to create a system-paced BCI*

Participants: Maureen Clerc, Joan Fruitet, Théodore Papadopoulo, Eoin Thomas.

An important factor in the usability of a brain computer interface (BCI) is the setup and calibration time required for the interface to function accurately. Recently, brain-switches based on the rebound following motor imagery of a single limb effector have been investigated as basic BCIs due to their good performance with limited electrodes, and brief training session requirements. In this work, a BCI is proposed which expands the methodology of brain-switches to design an interface composed of multiple brain-buttons. The algorithm is designed as a system paced interface which can recognise 2 intentional-control tasks and a no-control state based on the activity during and following motor imagery in only 3 electroencephalogram channels. An online experiment was performed over 6 subjects to validate the algorithm, and the results show that a working BCI can be trained from a single calibration session and that the post motor imagery features are both informative and robust over multiple sessions.

This work has been published in [24].

6.6.2. *An analysis of performance evaluation for motor-imagery based BCI*

Participants: Maureen Clerc, Matthew Dyson [Laboratoire de Neurosciences Cognitives, Marseille], Eoin Thomas.

In recent years, numerous brain–computer interfaces (BCIs) based on motor-imagery have been proposed which incorporate features such as adaptive classification, error detection and correction, fusion with auxiliary signals and shared control capabilities. Due to the added complexity of such algorithms, the evaluation strategy and metrics used for analysis must be carefully chosen to accurately represent the performance of the BCI. In this work, metrics are reviewed and contrasted using both simulated examples and experimental data. Furthermore, a review of the recent literature is presented to determine how BCIs are evaluated, in particular, focusing on the relationship between how the data are used relative to the BCI subcomponent under investigation. From the analysis performed in this study, valuable guidelines are presented regarding the choice of metrics and evaluation strategy dependent upon any chosen BCI paradigm.

This work has been published in [23].

6.6.3. *Bandit algorithms for faster task selection in BCI*

Participants: Maureen Clerc, Aurélien Emmanuel, Joan Fruitet [former Athena PhD student], Alexandra Carpentier [Sequel Project-Team, Inria Lille], Rémi Munos [Sequel Project-Team, Inria Lille].

Brain–computer interfaces (BCIs) based on sensorimotor rhythms use a variety of motor tasks, such as imagining moving the right or left hand, the feet or the tongue. Finding the tasks that yield best performance, specifically to each user, is a time-consuming preliminary phase to a BCI experiment. This study presents a new adaptive procedure to automatically select (online) the most promising motor task for an asynchronous brain-controlled button. We have developed for this purpose an adaptive algorithm UCB-classif based on the stochastic bandit theory and design an EEG experiment to test our method. We compare (offline) the adaptive algorithm to a naïve selection strategy which uses uniformly distributed samples from each task. We also run the adaptive algorithm online to fully validate the approach. By not wasting time on inefficient tasks, and focusing on the most promising ones, this algorithm results in a faster task selection and a more efficient use of the BCI training session. More precisely, the offline analysis reveals that the use of this algorithm can reduce the time needed to select the most appropriate task by almost half without loss in precision, or alternatively, allow us to investigate twice the number of tasks within a similar time span. Online tests confirm that the method leads to an optimal task selection. This study is the first one to optimize the task selection phase by an adaptive procedure. By increasing the number of tasks that can be tested in a given time span, the proposed method could contribute to reducing 'BCI illiteracy'.

This work has been published in [17].

6.6.4. *Enhancing visuospatial attention performance with brain-computer interfaces*

Participants: Thomas Brochier [Institut des Neurosciences de La Timone, Marseille], Maureen Clerc, Romain Trachel.

Brain-Computer Interfaces (BCI) can provide innovative solutions beyond the medical domain. In human research, visuospatial attention is often assessed from shifts in head or gaze orientation. However in some critical situations, these behavioral features can be dissociated from covert attention processes and brain features may indicate more reliably the spatial focus of attention. In this context, we investigate whether EEG signals could be used to enhance the behavioral performance of human subjects in a visuospatial attention task. Our results demonstrate that a BCI protocol based on adaptive or warning displays can be developed to shorten the reaction time and improve the accuracy of responses to complex visual targets. We performed offline and online tests demonstrating the validity of this type of approach.

This work was presented at conferences in the HCI community [35] and in the Neural Engineering community [34].

6.6.5. Verbal communication through brain computer interfaces

Participants: Maureen Clerc, Dieter Devlaminck, Claude Desnuelle [CHU de Nice l'Archet], Violaine Guy [CHU de Nice l'Archet], Manu Maby [Centre de Recherche Neurologique de Lyon], Jérémie Mattout [Centre de Recherche Neurologique de Lyon], Théodore Papadopoulo.

Brain Computer Interfaces (BCI) provide a way of communicating directly from brain activity, bypassing muscular control. We report some recent advances in a BCI communication system called the P300 speller, which is a virtual brain-operated keyboard. This system relies on electroencephalographic activity time-locked to the flashing of the desired letters. It requires calibration of the system, but very little training from the user. Clinical tests are being conducted on a target population of patients suffering from Amyotrophic Lateral Sclerosis, in order to confirm the usability of the P300 speller for reliable communication.

This work has been published in [26]. It is also the object of an intensive clinical study on 20 patients which we are currently conducting at Nice University Hospital.

BIOCORE Project-Team

6. New Results

6.1. Mathematical methods and methodological approach to biology

6.1.1. Mathematical analysis of biological models

6.1.1.1. Mathematical study of semi-discrete models

Participants: Jean-Luc Gouzé, Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard, Elsa Rousseau, Nicolas Bajoux.

Semi-discrete models have shown their relevance in the modeling of biological phenomena whose nature presents abrupt changes over the course of their evolution [99]. We used such models and analysed their properties in several practical situations that are developed in Section 6.2.2, most of them requiring such a modeling in order to take seasonality into account. Such is the case when the year is divided into a cropping season and a ‘winter’ season, where the crop is absent, as in our analysis of the sustainable management of crop resistance to pathogens [53] or in the co-existence analysis of epidemiological strains [21]. Seasonality also plays a big role in the semi-discrete modeling required for the analysis of consumers’ adaptive behavior in seasonal consumer-resource dynamics, where only dormant offspring survive the ‘winter’ [61].

6.1.1.2. Model design, identification and validation

Participants: Olivier Bernard, Francis Mairet.

One of the main families of biological systems that we have studied involves mass transfer between compartments, whether these compartments are microorganisms or chemical species in a bioreactor, or species populations in an ecosystem. We have developed methods to estimate the models of such systems [79]. These systems can be represented by models having the general structure popularized by [78], [84], and based on an underlying reaction network:

$$\frac{d\xi}{dt} = K r(\xi, \psi) + D(\xi_{in} - \xi) - Q(\xi)$$

We address two problems: the determination of the pseudo-stoichiometric matrix K and the modelling of the reaction rates $r(\xi, \psi)$.

In order to identify K , a two-step procedure has been proposed. The first step is the identification of the minimum number of reactions to be taken into account to explain a set of data. If additional information on the process structure is available, we showed how to apply the second step: the estimation of the pseudo-stoichiometric coefficients.

This approach has been applied to various bioproduction processes, among which activated sludge processes [77], anaerobic digestion [92], [106] and anaerobic digestion of microalgae [100]. Recently it was also used to reduce the ADM1 model in the case of winery effluent wastewater [24].

6.1.2. Metabolic and genomic models

Participants: Jean-Luc Gouzé, Madalena Chaves, Alfonso Carta, Ismail Belgacem, Olivier Bernard, Caroline Baroukh, Rafael Muñoz-Tamayo, Jean-Philippe Steyer.

Global stability for metabolic models and full Michaelis-Menten equations

With techniques of monotone and compartmental systems, we studied full (i.e. not reduced by any time-scale argument) Michaelis-Menten reactions or chains of reactions: we prove global stability when the equilibrium exists, and show that it may not exist. This fact has important consequences for reduction of metabolic systems in a coupled genetic-metabolic system [17].

Structural principles for the existence of limit cycles in two-dimensional piecewise affine models

Using concavity and continuity properties of Poincaré maps, we have derived some structural principles which link the topology of the transition graph to the existence, number and stability of limit cycles in a class of two-dimensional piecewise affine biological models [13].

Probabilistic approach for predicting periodic orbits in piecewise affine models

In the state transition graph, a *transition probability* between two nodes can be defined in terms of the parameters of the piecewise affine models. For a cyclic transition graph, this approach can be used to predict the most likely periodic orbit for a given a set of parameters [22].

Growth rate models in bacteria: piecewise affine systems with a dilution term

We have extended the class of piecewise affine systems to deal with dynamics dependent on dilution due to cell growth rate. Considering that growth rate is determined by two limiting factors (RNA polymerase and ribosomes), in [42] we propose and analyze a switched system with two piecewise quadratic modes. This is part of the PhD thesis of Alfonso Carta, and done in collaboration with IBIS project-team.

Transcription and translation models in bacteria

We study detailed models of transcription and translation for genes in a bacterium. With techniques of monotone systems, and time scale hypotheses, we can show the stability of the fast part of these systems, and reduce them to much smaller models [40], [39]. We also study other models of the global cellular machinery. This is part of the PhD theses of Ismael Belgacem, Alfonso Carta, and done in collaboration with IBIS project-team. Moreover, in collaboration with IBIS, we studied and experimentally validated the time scale reduction of the classical two-step model for gene expression [51]

Analysis of circadian rhythms in cyanobacteria

A hierarchy of models (from Boolean to continuous) was used in [23] to successively characterize the wiring structure, qualitative dynamical properties, and then perform parameter estimation on a model describing the system responsible for the circadian rhythm of cyanobacteria.

Interconnections of Boolean modules: asymptotic and transient behaviour

The asymptotic dynamics of high-dimensional networks (e.g., genetic) can be obtained from the interconnection of two input/output Boolean subnetworks, and the analysis of their attractors. This computational cost reducing method is described in [34]. Some extensions include the characterization of the attractors of the interconnected system in terms of invariant sets.

Structure estimation for Boolean models of gene regulation networks

The problem of estimating Boolean models of gene networks from few and noisy measurements is addressed in [41], joint work with C. Breindl and F. Allgöwer from the University of Stuttgart. The class of unate or canalizing Boolean functions is considered and represented by multi-affine polynomials, leading to a reformulation of the estimation problem as a mixed integer linear program.

Analysis of dynamical systems by combining discrete and continuous formalisms

The work reviewed in the HDR of M. Chaves [11] highlights methods of analysis that use and combine techniques from discrete and piecewise affine modeling formalisms, such as construction of the transition graph and its association with the parameters of the system. Some basic methods for generating a discrete transition graph from a given continuous system are described in the internship project of F. Todoran [75].

State estimation for gene networks

We address state estimation for gene regulatory networks with intrinsic and extrinsic noise at the level of single cells. We take the Chemical Master Equation (CME) with random parameters as a reference modeling approach, and investigate the use of stochastic differential model approximations for the construction of practical real-time filters (based on non-linear Kalman filtering) [43]. This is a collaboration with Ibis team.

Modelling the metabolic network in non balanced growth conditions

On the basis of the knowledge of the metabolic network, we propose a new methodology to go beyond the “balanced growth paradigm” (assuming that there is no storage within the cell). We have therefore a tool to represent the possible storage of some key biochemical compounds. This approach was applied to describe the effect of both a light cycle and a nitrogen starvation on the lipid accumulation [37]. The first stage of the approach consists in splitting the metabolic network into sub-networks, which are assumed to satisfy balanced growth condition. The left metabolites interconnecting the sub-networks are allowed to behave dynamically. Then, thanks to Elementary Flux Mode analysis, each sub-network is reduced to macroscopic reactions, for which simple kinetics are assumed. This approach was applied to the accumulation of lipids and carbohydrates of the microalgae *Tisochrysis lutea* under day/night cycles. The resulting model described accurately experimental data obtained in day/night conditions; it efficiently predicts the accumulation and consumption of lipids and carbohydrates.

6.2. Fields of application

6.2.1. Bioenergy

6.2.1.1. Modelling of microalgae production

Participants: Olivier Bernard, Antoine Sciandra, Frédéric Grognard, Philipp Hartmann, Rafael Muñoz-Tamayo, Ghjuvan Grimaud, David Demory, Frédéric Chazalon, Hubert Bonnefond, Jean-Philippe Steyer, Francis Mairet.

Experimental developments

Experiments have been carried out to study the effects of nitrogen limitation on the lipid production in microalgae and support model development. These experiments have been carried out in the Lagrangian simulator, under constant or periodic light and temperature, varying the total amount of light dose in the day. The response in terms of storage carbon (triglycerides and carbohydrates) has been observed.

Other experiments were carried out to reproduce the light percept by a cell in a raceway pond [74], that is a large-scale raceway-track shaped open-air photobioreactor with circulating medium. An electronic platform was developed to reproduce the flashing light which, from the hydrodynamical studies, is likely to happen in a raceway at the cell scale. The experiments show that the microalgae adapt their pigments to the average light that they have received.

The effect in the cell cycle of both the light periodic signal and a nitrogen limitation were studied. The strong interactions of the interactions between the different phases of the cell cycle through checkpoints was highlighted [104].

Finally, we have tested the effect of cement flue gas on microalgae growth and demonstrated that this CO₂ source can be used to feed microalgal industrial cultures [33].

These works have been carried out in collaboration with A. Talec, S. Rabouille, E. Pruvost and C. Combe (CNRS/UPMC -Océanographic Laboratory of Villefranchesur-Mer).

In collaboration with the IFREMER-PBA team (Nantes) we contributed to a study (within the Symbiose project) of the possible associations between microalgae and bacteria to enhance overall productivity [27].

Metabolism of carbon storage and lipid production

A macroscopic model for lipid production by oleaginous microalgae [10] has been previously proposed. This model describes the accumulation of neutral lipids (which can be turned into biofuel), carbohydrates and structural carbon. We now start to progressively dig deeper in the metabolism, with the objective to better predict carbohydrate and lipid accumulation [37], [64].

Modeling the coupling between hydrodynamics and biology

In collaboration with the Inria ANGE team, a model coupling the hydrodynamics of the raceway (based on multilayer Saint Venant system) with microalgae growth was developed [86]. This model is supported by the work of ANGE aiming at reproducing the hydrodynamics of the raceway, with a specific attention to the effect of the paddle wheel on the fluid.

Modeling the photosynthesis response to fast fluctuating light

The impact of the hydrodynamics on the light percept by a single cell was studied thanks to fluid dynamics simulations of a raceway pond [26]. The light signals that a cell experiences at the Lagrangian scale, depending on the fluid velocity, were then estimated. A Droop-Han model was used to assess the impact of light fluctuation on photosynthesis. A new model accounting for photoacclimation was also proposed [46]. Single cell trajectories were simulated by this tool, and the effect on photosynthesis efficiency was assessed using models of photosynthesis [94]. These results were compared to experimental measurements where the high frequency light was reproduced [74].

Modeling a microalgae production process

The integration of different models developed in the group [81], [101], [10] was performed to represent the dynamics of microalgae growth and lipid production in raceway systems, on the basis of the dynamical model developed to describe microalgal growth in a photobioreactor under light and nitrogen limitations. The strength of this model is that it takes into account the strong interactions between the biological phenomena (effects of light and nitrogen on growth, photoacclimation ...), temperature effect [85],[31] and the radiative transfer in the culture (light attenuation due to the microalgae).

Using these approaches, we have developed a model which predicts lipid production in raceway systems under varying light, nutrients and temperature [30]. This model is used to predict lipid production in the perspective of large scale biofuel production.

Finally, we provide guidelines for the design of experiments with high informative content that allows an accurate parameter estimation of this model, concerning the effect of temperature and light on microalgae growth. The optimal experiment design problem was solved as an optimal control problem. E-optimal experiments were obtained by using two discretization approaches namely sequential and simultaneous. Simulation results showed the relevance of determining optimal experimental inputs for achieving an accurate parameter estimation [50].

Nitrogen fixation by nitrogenotrophs

The fixation of nitrogen by *Croccosphaera watsonii* was represented with a macro metabolic model [44]. The main fluxes of carbon and nitrogen are represented in the cell. The accumulation of starch during the day to fuel the nitrogenase working in the absence of oxygen during the night was the key process to explain the nitrogen fixation. The strong influence of the cell cycle was also included in the model. Finally, the model was calibrated and validated with the data of 3 experiments carried out with different duration of the light period and daily dose. The model succeeded to efficiently reproduce the experimental data.

This work is done in collaboration with Sophie Rabouille (CNRS-Océanographic Laboratory of Villefranche-sur-Mer).

Including phytoplankton photoadaptation into biogeochemical models

The complexity of the marine ecosystem models and the representation of biological processes, such as photoadaptation, is very challenging to tackle so that their representation remains an open question. We compared several marine ecosystem models with increasing complexity in the phytoplankton physiology representation in order to assess the consequences of the complexity of photoadaptation models in biogeochemical model predictions. Three models of increasing complexity were considered, and the models were calibrated to reproduce ocean data acquired at the Bermuda Atlantic Time-series Study (BATS) from in situ JGOFS (Joint Global Ocean Flux Study) data. It turns out that the more complex models are trickier to calibrate and that intermediate complexity models, with an adapted calibration procedure, have a better prediction capability [15].

This work is done in collaboration with Sakina Ayata (UPMC-Océanographic Laboratory of Villefranche-sur-Mer).

6.2.1.2. Control and Optimization of microalgae production

On-line monitoring

Interval observers give an interval estimation of the state variables, provided that intervals for the unknown quantities (initial conditions, parameters, inputs) are known [7]. Several developments were carried out in this direction to improve the design and performances of interval observers. The approach has been applied to estimation of the microalgae growth and lipid production within a production process [28].

Optimization of the bioenergy production systems

Based on simple microalgae models, analytical optimization strategies were proposed. We first focused on the optimal operating conditions for the biomass productivity under day/night cycles using Pontryagin's maximum principle (assuming a periodic working mode) [25].

On the other hand, we assessed strategies for optimal operation in continuous mode using the detailed model for raceways [49], [30]. Two strategies were developed. The first one resides in solving numerically an optimal control problem in which the input flow rate of the raceway is calculated such that the productivity in microalgae biomass is maximized on a finite time horizon. In the second strategy, we aimed at translating the optimization problem into a regulation problem. We proposed a simple operational criterion that when integrated in a strategy of closed-loop control allows to attain biomass productivities very near to the maximal productivities obtained with the optimal control. We demonstrated that the practical advantages for real implementation makes our proposed controller a suitable control strategy for optimizing microalgae production in raceways.

We also propose a nonlinear adaptive controller for light-limited microalgae culture, which regulates the light absorption factor (defined by the ratio between the incident light and the light at the bottom of the reactor). We show by numerical simulation that this adaptive controller can be used to obtain near optimal productivity under day-night cycles [47].

Interactions between species

Large scale culture of microalgae for bioenergy involves a huge biodiversity (different mutants, invasion, growth-promoting bacteria [96]...). Control of such system requires to consider the interactions between the different species.

In the framework of the ANR Facteur 4 project, we propose to drive this competition exploring different strategies in order to select species of interest.

We have proposed an adaptive controller which regulates the light at the bottom of the reactor [48]. When applied for a culture with n species, the control law allows the selection of the strain with the maximum growth rate for a given range of light intensity. This is of particular interest for optimizing biomass production as species adapted to high light levels (with low photoinhibition) can be selected.

Other strategies (e.g. periodic temperature stress) are now under investigation through simulations (in order to design selection experiments that will be performed at LOV) and model analysis.

Finally, in a more theoretical framework, we studied how to select as fast as possible a given species in a chemostat with two species at the initial instant. Using the Pontryagin maximum principle, we have shown that the optimal strategy is to maintain the substrate concentration to the value maximizing the difference between the growth rates of two species [66].

6.2.2. Design of ecologically friendly plant production systems

6.2.2.1. Controlling plant pests

Participants: Frédéric Gognard, Ludovic Mailleret, Suzanne Touzeau, Mickaël Teixeira-Alves, Nicolas Bajeux.

Optimization of biological control agent introductions

The question of how many and how frequently natural enemies should be introduced into crops to most efficiently fight a pest species is an important issue of integrated pest management. The topic of natural enemies introductions optimization has been investigated for several years [9] [105], unveiling the crucial influence of within-predator density dependent processes. Because contrarily to predatory biocontrol agents, parasitoids may be more prone to exhibit positive density dependent dynamics rather than negative ones, the current modeling effort concentrates on studying the impact of positive predator-predator interactions on the optimal introduction strategies [72]. Connected experimental research is also being pursued in the laboratory on *trichogramma spp.* which tends to show positive density dependence because of demographic stochasticity [35], and the PhD thesis of Thibaut Morel Journel (UMR ISA) has just started on this topic. Non-impulsive positive feedback control of predator-prey systems in that framework was also addressed in [45].

Food source diversity and classical biological control efficiency using generalist natural enemies

Because generalist biocontrol agents can feed on different food sources like, e.g. a given pest and pollen, they are capable of surviving pest absence within crops and, when supplied with different food types, generalist biocontrol agents are expected to thrive. However, feeding on different food sources means that a given individual cannot feed on each food source at the same moment, which thus potentially reduces the overall predation pressure imposed by the natural enemy population. We exhibited conditions under which the predator distraction effects can dominate the demographic response of the predator populations, potentially disrupting pest control [12]. Such results were at the center of Mickaël Teixeira Alves's PhD thesis.

Plant compensation, pest control and plant-pest dynamics

Introducing a plant compartment into our models, we first focused on plant-insect interactions and showed how the level and timing of the pest invasion and pests control interventions could have important effects on the plant's growth pattern and its final biomass. We then modelled plant compensation, which is the process by which some plants respond positively to recover from the effects of pest injury. We have shown that depending on plants and pests characteristics, as well as the level of pest attack, plant overcompensation may or may not happen [97].

This work is part of the PhD thesis of Audrey Lebon (Cirad), and done in collaboration with Yves Dumont (Cirad).

6.2.2.2. *Controlling plant pathogens*

Participants: Frédéric Gognard, Ludovic Mailleret, Suzanne Touzeau, Elsa Rousseau.

Sustainable management of plant resistance

Because in addition to being eaten, plants can also get sick, we studied other forms of biological control dedicated to fight plant pathogens. One such method is the introduction of plant strains that are resistant to one pathogen. This often leads to the appearance of virulent pathogenic strains that are capable of infecting the resistant plants. It is therefore necessary to develop ways of introducing such resistance into crop production without jeopardizing its future efficiency. Considering plant viruses, we computed the proportion of resistant plants that should be cropped together with the non-resistant ones in a seasonal model, in order to optimize the resistance for production or patrimonial objectives [53]. The study of factors influencing resistance breakdown from the within-plant to the landscape level is the topic of Elsa Rousseau's PhD thesis, with emphasis both on experimental and modelling approaches. Experiments have been held in Avignon to determine the respective impacts of selection and genetic drift on resistance breakdown.

This work is done in collaboration with Frédéric Fabre and Benoit Moury (INRA Avignon).

Eco-evolutionary dynamics of plant pathogens in seasonal environments

Understanding better pathogen evolution also requires to understand how closely related plant parasites may coexist. Indeed, such coexistence is widespread and is hardly explained through resource specialization. We showed that, in agricultural systems in temperate environments, the seasonal character of agrosystems can induce complex plant-pathogens dynamics [98] and is an important force promoting evolutionary diversification of plant pathogens [93]. Plant parasites reproduction mode may also strongly interact with seasonality. In this

context, we investigated the influence of cyclical parthenogenesis, i.e. the alternation of sexual and asexual reproduction phases, on the eco-evolutionary dynamics of plant parasites [59], [60], [21].

This work is part of the PhD thesis of Magda Castel (Agrocampus Ouest) and is done in collaboration with Frédéric Hamelin (Agrocampus Ouest).

6.2.3. Biological depollution

6.2.3.1. Coupling microalgae to anaerobic digestion

Participants: Olivier Bernard, Antoine Sciandra, Jean-Philippe Steyer, Frédéric Grognard, Philipp Hartmann, Francis Mairet.

The coupling between a microalgal pond and an anaerobic digester is a promising alternative for sustainable energy production and wastewater treatment by transforming carbon dioxide into methane using light energy. The ANR Symbiose project is aiming at evaluating the potential of this process [108], [107].

In a first stage, we developed models for anaerobic digestion of microalgae. Two approaches were used: first, a dynamic model has been developed trying to keep a low level of complexity so that it can be mathematically tractable for optimisation [100]. Considering three main reactions, this model fits adequately the experimental data of an anaerobic digester fed with *Chlorella vulgaris* (data from INRA LBE). On the other hand, we have tested the ability of ADM1 [109] (a reference model which considers 19 biochemical reactions) to represent the same dataset. This model, after modification of the hydrolysis step [102] has then been used to evaluate process performances (methane yield, productivity...) and stability through numerical simulations.

6.2.3.2. Life Cycle Assessment

Participants: Olivier Bernard, Jean-Philippe Steyer.

This work is the result of a collaboration with Laurent Lardon and Arnaud Helias of INRA-LBE through the co-supervision of Pierre Collet's PhD thesis [88].

An analysis of the potential environmental impacts of biodiesel production from microalgae has been carried out using the life cycle assessment (LCA) methodology [95]. This study has allowed to identify the obstacles and limitations which should receive specific research efforts to make this process environmentally sustainable. This study has been updated and the effects of technological improvements (leading to higher productivities) have been compared to the source of electricity. It turns out that the overall environmental balance can much more easily be improved when renewable electricity is produced on the plant [91], [90]. As a consequence, a new paradigm to transform solar energy (in the large) into transportation biofuel is proposed, including a simultaneous energy production stage. This motivated the design of the purple sun ANR-project.

These studies have allowed to identify the obstacles and limitations which should receive specific research efforts to make this process environmentally sustainable [65].

A LCA has been carried out to assess the environmental impact of methane production by coupling microalgae and anaerobic digestion. The study highlights the limitation derived by the low biodegradability of the considered microalgae [89] which induces a large digester design and thus more energy to mix and heat it.

These works have been carried out in collaboration with E. Latrille and B. Sialve (INRA - Laboratory of Environmental Biotechnology, Narbonne).

6.2.4. Models of ecosystems

6.2.4.1. Optimality/games in population dynamics

Participants: Frédéric Grognard, Ludovic Mailleret, Pierre Bernhard.

Adaptive behavior in seasonal consumer-resource dynamics

In this work we studied the evolution of a consumer-resource (or predator-prey) system with seasonal character of the dynamics. We specified two main parts of the process. First, we considered the system during one season with a fixed length: the prey lay eggs continuously and the predators lay eggs or hunt the prey (choose their behavior) according to the solution of an optimal control problem [76]. We then showed that, in most situations, mutants can take advantage of their low frequency and fare better than the residents. Over the course of a large number of seasons, the mutants replace the residents, only to find themselves applying the original resident behavior [61].

Optimal foraging and residence times variations

Charnov's marginal value theorem (MVT) [87] is a central tenet of ecological theory. In fragmented environments, the MVT connects the quality and distribution of patches to the optimal time an individual should spend on any patch, and thus the rate of movement in the habitat. Unfortunately, it does not offer explicit predictions regarding how changing habitat quality would affect residence times. In this work, we answer that question in a very general setting, for habitats with homogeneous or heterogeneous patches and with general fitness functions. We then particularize it to the resource consumption framework and indicate how the residence times variations relate to the curvatures of the functional responses,[20].

This last work is done in collaboration with Vincent Calcagno and Eric Wajnberg (INRA Sophia Antipolis)

The handicap paradox

We have investigated the "handicap paradox" of sexual selection, and more specifically revisited Grafen's mathematical models of Zahavi's "handicap principle". The paradox is that in many species, male secondary sexual characters that clearly attract the females are so developed as to be a handicap to the male's viability, and therefore should be counter-selected by evolution. Zahavi's explanation, made mathematical by Grafen, is that if this secondary sexual character is a signal to the female of the male's quality that she cannot observe otherwise, if this signal were costless, it could be cheated, a low quality male being induced to mimic the signal of a high quality one. We have cast this problem into a signaling game, using the bayesian equilibrium of game theory. This easily shows that indeed, under mild conditions, at equilibrium the signal should be "costly". We have developed several models inspired by Grafen, and to a lesser extent Getty, with explicit solutions, and explained why an undesirable feature appeared in Grafen's model (as well as in one of ours) and proposed a model free of this artifact [19].

6.3. Software design

6.3.1. *Odin*

Participants: Olivier Bernard, Méline Gautier.

Over the years, BIOCORE has been developing a software framework for bioprocess control and supervision called **ODIN** [80]. This C++ application (working under Windows and Linux) enables researchers and industrials to easily develop and deploy advanced control algorithms through the use of a Scilab interpreter [82], [83]. It also contains a Scilab-based process simulator which can be harnessed for experimentation and training purposes. ODIN is primarily developed in the C++ programming language and uses CORBA to define component interfaces and provide component isolation. ODIN is a distributed platform, enabling remote monitoring of the controlled processes as well as remote data acquisition. Recently, a software development effort has been directed to the graphical user interface, a synoptic view component, new drivers for the experimental hardware and integration of the PlantML data exchange format. ODIN has been tested on four different processes and has been set up with Eric Latrille to supervise the 66m² high rate pond at the LBE, INRA Narbonne.

6.3.2. *In@lgae*

Participants: Etienne Delclaux, Francis Mairet, Olivier Bernard.

The simulation platform In@lgae is jointly developed with the Inria Ange team. Its objective is to simulate the productivity of a microalgae production system, taking into account both the process type and its location and time of the year. A first module (Freshkiss) developed by Ange computes the hydrodynamics, and reconstructs the Lagrangian trajectories perceived by the cells. Coupled with the Han model, it results in the computation of an overall photosynthesis yield. A second module is coupled with a GIS (geographic information system) to take into account the meteorology of the considered area (any location on earth). The evolution of the temperature in the culture medium together with the solar flux is then computed. Finally, the productivity in terms of biomass, lipids, pigments together with CO₂, nutrients, water consumption, ... are assessed. The productivity map which is produced can then be coupled with a resource map describing the availability in CO₂ nutrients and land.

CASTOR Team

6. New Results

6.1. High order approximation of the two fluid Braginskii model

Participants: Sebastian Minjeaud, Richard Pasquetti.

We work on a two fluid physical model developed in close connection with Ph. Ghendrih (IRFM). It is based on the electrostatic assumption, i.e. the magnetic field is given (the magnetic field induced by the plasma itself is negligible), on the hypothesis of electroneutrality (the density of ions and electrons are proportional) and on the Braginskii closure. On the basis of the conservation equations of density, electron and ion velocities, electron and ion temperatures and electrical charges, a set of 10 non-linear and strongly anisotropic coupled partial differential equations (PDE) can be set up. A high order Fourier-SEM (Spectral Element Method) code is currently developed to address this problem. This Fourier-SEM code is close to be operational for the full set of PDEs in a 3D toroidal geometry. The torus section is discretized with quadrangular elements and Fourier expansions are used in the toroidal direction. In time one uses an RK3 (third order Runge-Kutta) IMEX (Implicit-Explicit), so that the Lorentz terms are handled implicitly. The capability of this code to handle a strongly anisotropic diffusion in a 3D toroidal geometry has already been tested. The Braginskii closure has been implemented. The Bohm boundary conditions at the plates are also considered. In 2013, we worked on a parallel version of the code and on the robustness of our algorithms, to be able to make long time computations, e.g. a few hundreds of thermal times.

6.1.1. Parallelization of the full Braginskii (FBGKI) code.

A first parallel version of the FBGKI code is now operational. Tests were made on the Computational center of the University of Nice-Sophia Antipolis. Tests on a large number of processors have however not yet been carried out, since presently our goal is to improve the robustness of our algorithms. Our parallelization strategy is based on a domain decomposition technique in the poloidal plane, where the spectral element approximation is local. On the contrary, in toroidal direction the approximation is global since based on Fourier expansions.

6.1.2. Numerical stabilization.

A spectral vanishing viscosity (SVV) technique was implemented in the sequential version of the code. Such a stabilization technique relies on the idea of introducing viscosity in the high frequency range of the spectral element / Fourier approximation. Such an approach was first proposed for hyperbolic problems, typically the Burgers equation (E. Tadmor, 1989). Later on, it was used for the large-eddy simulation of turbulent flows. Thus, we have a large experience of the SVV stabilization for the computation of turbulent wake flows.

6.1.3. Projection techniques.

A projection technique is used to enforce the divergence free constraint of the current. Projection techniques have been developed for a long time, in the frame of the Navier-Stokes equations to provide efficient algorithms when incompressible flows are concerned. For the Braginskii system, it appears natural to make use of such techniques for the current. Different projection techniques have been implemented in the FBGKI code, from the most classical one (Chorin-Temam, 1969) to the most recent. It turns out however that using projection techniques is less straightforward for Braginskii than for Navier-Stokes. We actively work on this point in order to cure some not yet understood failures of convergence with the time-step.

In the frame of the Eurofusion program, it is planned to check this version of the code on a simple configuration proposed by the EPFL (Paolo Ricci) where experimental as well as numerical results are available.

6.2. Equilibrium reconstruction and current density profile identification

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

EQUINOX is a real-time equilibrium reconstruction code. It solves the equation satisfied by the poloidal flux in a computation domain, which can be the vacuum vessel for example, using a P1 finite element method and solves the inverse problem of the identification of the current density profile by minimizing a least square cost-function. It uses as minimal input the knowledge of the flux and its normal derivative on the boundary of the computation domain. It can also use supplementary constraints to solve the inverse problem: interferometric, polarimetric and MSE measurements. Part of the work reported here has been done in the frame of a RTM-JET contract [2]

6.2.1. Direct use of the magnetic measurements

The code EQUINOX was not originally designed to take as magnetic inputs directly the magnetic measurements, as it should be the case in the ITM (Integrated Tokamak Modeling European platform), but some outputs from the real-time codes APOLO at ToreSupra and XLOC at JET. These codes provide EQUINOX with the values of the flux and its normal derivative on a closed contour defining the boundary of the computation domain (this contour can be the limiter for example). As a consequence the main difficulty arising in the objective of integrating the code EQUINOX in the ITM structure is to interpolate between the magnetic measurements (flux loops and poloidal B-probes) with a machine independent method. A solution to do this is to use toroidal harmonics functions as a basis for the decomposition of the poloidal flux in the vacuum region in complement to the contribution of the PF coils. The first version of the algorithm implementing this method for EQUINOX-ITM developed in 2012 has been updated and tested during 2013:

- WEST and JET: This method can provide an alternative tool, comparable to APOLO (for Tore Supra) and FELIX (for JET), to compute the plasma boundary in real time from the magnetic measurements. Some twin experiments for WEST have been successfully conducted. In a first step the equivalents of magnetic measurements were generated using the free boundary equilibrium code CEDRES++. In a second step these measurements were used by the toroidal harmonics algorithm to reconstruct the plasma boundary. Additional calculations aiming at validating the design of the WEST magnetic diagnostics have been performed. They consisted in checking the equilibrium reconstruction accuracy with respect to: (i) a reduced number of magnetic sensors; (ii) noise on magnetic sensor and/or current measurements. Then, experiments on the possibility to reconstruct not only the plasma boundary but also the current density have been conducted. A paper on this subject is accepted for publication [13]. The same algorithm has been tested using real JET measurements in order to provide an equilibrium reconstruction code that directly uses the magnetic measurements instead of using FELIX as an intermediate preprocessing of the measurements.
- EFDA-ITM (Task WP13-ITM-IMP12-ACT3): EQUINOX-ITM has been upgraded and tested on the new gateway machine of the ITM. The Kepler actor was tested and used on 3 different tokamaks (JET, Tore Supra and WEST) (with F. Imbeaux, T. Aniel, P. Moreau, E. Nardon (CEA)). A benchmark work is on going between the codes Equal, Efit and Equinox on JET shot 74221 (with Dimitriy Yadykin and Wolfgang Zwingmann).

6.3. Evolutive equilibrium and transport coupling and optimization of scenarii

Participants: Jacques Blum, Cédric Boulbe, Blaise Faugeras.

6.3.1. New developments in the direct evolutive version of CEDRES++

6.3.1.1. External circuits and saddle currents in the blankets

In the previous version of the free boundary equilibrium code CEDRES++, each PF-coil (Poloidal Field Coil) was considered separately. In the evolutive version, a voltage was applied to each coil. In the machine, PF-coils can be connected in series or in parallel with one or several power supplies. In order to consider more realistic configurations of the PF system, the model used in CEDRES++ has been generalized to circuits involving several coils and supplies connected in series or in parallel. This model has been implemented in CEDRES++ and has been tested on simple configurations with circuits composed of one supply and several coils connected in series. More complicated configurations like circuits with several supplies and coils in series and in parallel in the same circuit have to be tested. This will be done on a WEST test case. A model for saddle currents in the blankets has also been implemented. This model is actually under validation on DEMO geometry.

6.3.1.2. Coupling CEDRES++ with a feedback controller (task ITM-WP13-ITM-IMP12-ACT1-T3)

Cedres++ has been successfully coupled with a controller generated from the true TCV hybrid Simulink controller in an ITM (Integrated Tokamak Modeling) workflow. The "yoyo" discharge (shot 40475) has been reproduced. In Figure 1, the vertical position of the magnetic axis simulated matches the experimental one.

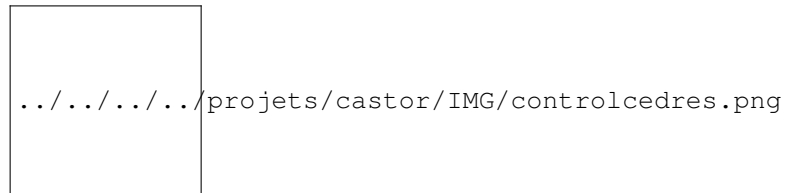


Figure 1. Simulation of Yoyo discharge on TCV - Comparison between Z axis simulated and Z axis obtained from experiments

6.3.1.3. Cedres++ - transport coupling

Last year, different algorithms coupling free boundary equilibrium solvers and transport solvers (CEDRES++-diff, CEDRES++-CRONOS, CEDRES++-ETS, FREEBIE-CRONOS) have been developed. The ETS-C coupling between CEDRES++ and the transport solver under the ITM environment has been finalized this year. A simulation of a VDE test case has been performed (task WP13-ITM-IMP12-ACT1-T2). A benchmark between the different strategies has been performed in order to validate the numerical methods required to ensure stability of the coupling system and to compare the physical simulations of each model. A benchmark between CEDRES++-diff solving the resistive diffusion equation coupled to CEDRES and the CEDRES-CRONOS coupling has been performed on an ITER test case. Some divergences between the two codes appear and are not fully understood despite long investigations. This difficulty has led us to delay the introduction of non inductive terms in the resistive diffusion equation implemented in CEDRES++-diff. These developments will be realized when the different coupling strategies will be fully validated.

6.3.2. Research of optimal trajectories for the preparation of Tokamak discharges

A new approach has been developed for the optimization of dynamic plasma scenarios in tokamaks. This task has been formulated as an optimal control problem, using numerical solution methods for optimization problems with PDE constraints. Due to free boundary setting, a new linearization of the non-linear equations has been introduced, which is consistent with the numerical discretization. It is this consistency that guarantees that the method converges to the optimum.

6.4. Parallel Kelvin-Helmholtz-like instability in edge plasma

Participants: Hervé Guillard, Boniface Nkonga, Marco Bilanceri, Giorgio Giorgiani.

A large part of this year activities have been devoted to the investigation of the Kelvin-Helmholtz-like instabilities that can be triggered at the core/SOL transition, the sheath acceleration at the limiter or divertor plates leading to a radial shear for the velocity. Linear stability analysis developed in Schwander et al ² actually reveals that unstable modes at the edge-core transition can develop in the presence of core rotation. This study was also an opportunity for a benchmarking comparison with the TOKAM3X code developed in IRFM and at Marseille. Both codes have confirmed the linear stability analysis and have shown that large fluctuations grow in the shear layer downstream of the limiter on the LFS (Low Field Side), the growth of these fluctuations being accompanied by a radial drift away from the limiter. Fig. 2 displays a 3D representation of these unstable

²Schwander et al., J. Nucl. Materials, doi:10.1016/j.jnucmat.2010.10.073 2011

density fluctuations. Apart from the physical results, this study has also shown the large sensitivity of the solutions to the discretization and to the implementation of the Bohm's boundary conditions. It has also shown that the study of these parallel KH like instabilities is a very demanding benchmark : these simulations require large meshes and since the growth rate of these instabilities is very weak, this results in an extremely long simulation time involving an extremely large number of time steps. In the future, it is planned to investigate the saturation of the instability as well as its possible presence in diverted plasmas.

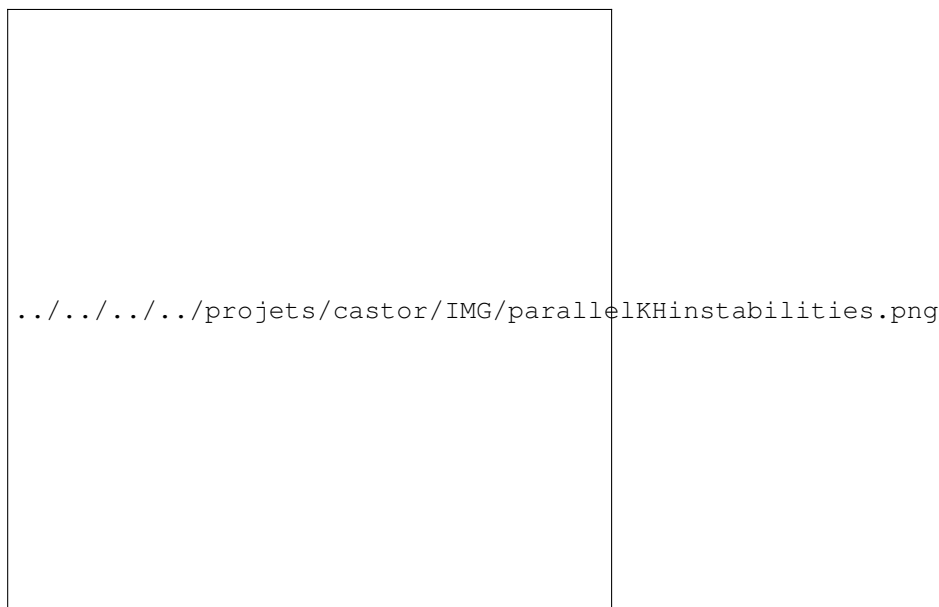


Figure 2. 3D representation of unstable density fluctuations in edge plasma tokamak with limiter. The core plasma rotates in the anti-clockwise direction $M//central=0.75$, safety factor $q=6$

6.5. Development of a two temperature model

Participants: Hervé Guillard, Afeintou Sangam, Elise Estibals.

A two temperature (ions - electrons) version of the code is in development. At present an approximate Riemann solver using the total energy equation and the electron entropy as main variables has been designed. This Riemann solver has been validated against standard shock tube problems and incorporated in the PlaTo platform. The implementation of this solver in toroidal geometry is in progress.

6.6. Implementation of a Taylor-Galerkin stabilized Finite Element

Participants: José Costa, Marie Martin, Boniface Nkonga.

The theoretical part of Taylor-Galerkin (TG) stabilized strategy applied to MHD and reduced MHD modeling has been realized. The final method amounts to add in the formulation, a self-adjoint operator associated to the most critical hyperbolic component of the system to be solved. The design of the critical contours and the identification of associated waves to be stabilized is problem dependent and related to the Jacobian matrix. A simplified version has been developed for reduced MHD and takes into account the high anisotropy of strongly magnetized plasma under consideration here. This first implementation of the TG stabilization in Jorek, has made possible efficient and robust simulations of Edge Localized Modes (Elms) and their mitigation by Resonant Magnetic Perturbations (RMP) and pellets injections. Work under progress will use more elaborated TG formulations that will be applied to reduced and full MHD models.

6.7. Development of a full MHD Modeling

Participants: José Costa, Jeaniffer Vides, Boniface Nkonga.

The single fluid full MHD numerical model has been developed. The divergence free constraint on the magnetic field is achieved by introduction of a potential vector. The use of the potential vector has the additional advantage that the toroidal component is the magnetic flux of the Grad-Shafranov equilibrium. Therefore, using the same finite element for the computation of initial equilibrium and the evolution of perturbed system, the numerical scheme is well balanced when the projection of the momentum equation use a component parallel to the magnetic field. Indeed, at the discrete level the projection is exactly orthogonal to equilibrium sub-space. Using the potential vector as variable introduces third order derivatives in the system and classical C0 finite elements cannot be directly applied. This is why our finite element strategy uses shape/test functions whose derivatives have global continuity in space. Finite element method is designed for poloidal plane discretization using quadrangles or triangles. Validations have been performed for internal kink and tearing modes instabilities in tokamak with a circular plasma. For this configuration, all magnetic surfaces are closed and simple boundary conditions are used. Future work will address X-point configurations with Bohm boundary conditions.

6.8. Environmental and Astrophysical flows

Participants: Hervé Guillard, Boniface Nkonga, Marco Bilanceri, Maria-Vittoria Salvetti [University of Pisa, Italy], Karim Elhakim [University Ains Shams, Egypt].

The numerical approximation of a model coupling the shallow-water equations with a sediment transport equation for the morphodynamics has been studied. In shallow-water problems, time advancing can be carried out by explicit schemes. However, if the interaction with the mobile bed is weak, the characteristic time scales of the flow and of the sediment transport can be very different introducing time stiffness in the global problem. For this case, it is of great interest to use implicit schemes. The time integration strategy that we have devised is based on a defect-correction approach and on a time linearization, in which the flux Jacobians are computed through automatic differentiation. This work has been published in this reference ³. The aim of the present work is to investigate the behavior of this time scheme for different Riemann solvers, sediment transport models and situations related to environmental flows [12]. This activity takes place in the framework of the Euromediterranée 3+3 MedLagoon program and a PHC Imhotep program. A preliminary work has begun to apply this strategy to the study of the Burulus lake in Egypt.

6.9. Ionospheric plasma

Participants: Didier Auroux, Sebastian Minjeaud.

In order to guarantee the integrity of the european positioning system Galileo, it is fundamental to identify all the potential sources of system unavailability. One of the main sources that has been identified is the phenomenon of ionospheric scintillations which causes radio frequency signal amplitude and phase variations when satellite signals pass through the ionosphere. Scintillations appear as the turbulent aspect of a larger disturbance of the ionospheric plasma density, which has the shape of a plasma bubble. In this context and in the framework of the ANR IODISSEE, a model hierarchy aimed at representing the evolution of the ionospheric plasma was proposed (Besse and al., 2004). It is based on an asymptotic analysis of the Euler-Maxwell system thanks to typical scales of the physical parameters involved in this framework. Among these models the simplest, referred to as the Striation model, describes the evolution of the quasineutral plasma in a plane perpendicular to the earth magnetic field. The magnetic field is assumed constant, and both electron and ions inertia are neglected. In this model the mobility of charge particles is assumed infinite along the magnetic field lines so that they constitute equipotential for the electric field. This property allows the computation of the electric field by means of a two dimensional elliptic equation with coefficients integrated along the magnetic field lines. This equation is coupled to either a two or a three dimensional transport equation for the evolution of the plasma density.

³Linearized implicit time advancing and defect correction applied to sediment transport simulations Marco Bilanceri; François Beux; Imad Elmahi; Hervé Guillard; Maria Vittoria Salvetti *Computers and Fluids*, elsevier, 2012, 63, pp. 82-104

6.9.1. Data assimilation

We worked on data-models coupling method to identify the parameters of the Striation model (especially, the initial data for the electronic density and the ion/neutral collision frequency). Some measurements acquired during the mission of satellite DEMETER will constitute the set of observed data. We consider this problem from an optimal control point of view. We define a cost function measuring the misfit between the observed data and the corresponding model states. This function can be seen as a function of only the input model parameters. The previous inverse problem is then equivalent to minimizing this cost function. Of course, this problem can be ill posed (over or under-determined, non convex...) and we need to add some regularization terms (mainly Tikhonov terms), using some a priori estimation of the model parameters. The effective minimization of the cost function (in order to estimate the best possible set of model parameters) relies on the computation of the adjoint state. Thanks to the help of L. Hascoet, the adjoint of the Striation code was derived and validated with the automatic differentiation tool TAPENADE. We obtained the first results of coefficients identification in very simple situations.

6.9.2. Wave Propagation

The electronic density fluctuations of the ionospheric plasma have been identified as the main causes of the scintillation phenomena since they induce some variations of the amplitudes and phases of the signals passing through the ionosphere. These fluctuations have indeed a direct influence on the refractive index of the medium. A code was developed to simulate the propagation of wave signals in the perturbed ionosphere (whose representation is obtained thanks to the Striation code). We chose to use the method of the Rytov approximations which allow to obtain sufficiently accurate results (since, e.g., it takes into account the diffraction due to the small structures) within a reasonable computational time (contrary to the resolution of the whole Maxwell system). This work was carried out during the Master 2 internship of Gonzalo José Carracedo Carballal (advised with P. Lafitte, Ecole Centrale Paris).

6.10. Mesh adaptive MG Methods

Participants: Gautier Brethes [Projet Ecuador], Alain Dervieux, Olivier Allain [Lemma].

Anisotropic tetrahedrization, Continuous metric

This activity concerns the use of mesh adaptation and multigrid for simplified plasma models in the context of ANEMOS ANR project.

6.11. Turbulence models

Participants: Alain Dervieux, Bruno Koobus [University of Montpellier 2], Carine Moussaed [University of Montpellier 2], Maria-Vittoria Salvetti [University of Pisa], Stephen Wornom [Lemma], Marianna Braza [IMF-Toulouse].

Large Eddy Simulation, Variational Multi-scale, hybrid models, unstructured meshes, vortex shedding

The purpose of our works in hybrid RANS/LES is to develop new approaches for industrial applications of LES-based analyses. This year, a lot of experiments have validated the dynamic version of our VMS-LES. The quality of simulations is either comparable to non-dynamic, or better. In the foreseen applications (aeronautics, hydraulics), the Reynolds number can be as high as several tenth millions, a far too large number for pure LES models. However, certain regions in the flow can be much better predicted with LES than with usual statistical RANS (Reynolds averaged Navier-Stokes) models. These are mainly vortical separated regions as assumed in one of the most popular hybrid model, the hybrid Detached Eddy Simulation model. Here, "hybrid" means that a blending is applied between LES and RANS. The french-italian team is working on a novel type of hybrid model between the VMS-LES model and a $k - \varepsilon$ one. The team has this year concentrated on the shift between the RANS boundary region and the VLES boundary one. This is also the problematic on the IDDES studies. We are working on propositions relying not only on the value of the RANS viscosity but also on its gradient. A paper is in preparation on this subject.

COFFEE Project-Team (section vide)

DEMAR Project-Team

6. New Results

6.1. Modelling and Identification

6.1.1. *Emergence of Motor Synergy in Reaching Task via Tacit Learning -computational motor control*

Participants: Mitsuhiro Hayashibe, Shingo Shimoda [RIKEN,Japan].

The dynamics of multijoint limbs often causes complex dynamic interaction torques which are the inertial effect of other joints motion. It is known that Cerebellum takes important role in a motor learning by developing the internal model. We propose a novel computational control paradigm in vertical reaching task which involves the management of interaction torques and gravitational effect. The obtained results demonstrate that the proposed method is valid for acquiring motor synergy in the system with actuation redundancy and resulted in the energy efficient solutions. It is highlighted that the tacit learning in vertical reaching task can bring computational adaptability and optimality with model-free and cost-function-free approach differently from previous studies.

6.1.2. *Anatomy Transfer*

Participants: Dicko Ali-Hamadi, Tiantian Liu, Benjamin Gilles, Ladislav Kavan, Francois Faure, Olivier Palombi, Marie-Paule Cani.

Characters with precise internal anatomy are important in film and visual effects, as well as in medical applications. We propose the first semi-automatic method for creating anatomical structures, such as bones, muscles, viscera and fat tissues. This is done by transferring a reference anatomical model from an input template to an arbitrary target character, only defined by its boundary representation (skin). The fat distribution of the target character needs to be specified. We can either infer this information from MRI data, or allow the users to express their creative intent through a new editing tool. The rest of our method runs automatically: it first transfers the bones to the target character, while maintaining their structure as much as possible. The bone layer, along with the target skin eroded using the fat thickness information, are then used to define a volume where we map the internal anatomy of the source model using harmonic (Laplacian) deformation. This way, we are able to quickly generate anatomical models for a large range of target characters, while maintaining anatomical constraints.

6.1.3. *Center of Mass Estimation in Multicontact Situations: Simulation*

Participants: Alejandro González, Mitsuhiro Hayashibe, Emel Demircan [Stanford Univ.], Philippe Fraisse.

Center of mass (CoM) estimation can be used to evaluate human stability during rehabilitation. A personalized estimation can be obtained using the serial equivalent static chain (SESC) method, calibrated using a series of static postures. The estimation accuracy is dependent on the number and quality of poses used during calibration. Currently, this limits the method's application to unimpaired individuals. We present a preliminary study of a SESC identified in a multi-contact scenario during a Sit-to-Stand task. Stanford's SAI (Simulation and Active Interface) platform was used to emulate human motion and predict relevant reaction forces. The CoM estimation obtained is valid for motions similar to those used during identification. Since the SAI's human model is fully defined, in terms of mass and limb lengths, its exact center of mass is known. Using a 3-dimensional model, the estimated mean error was less than 26 mm for a Sit-to-Stand task involving displacements along all axes. As such, personalized CoM estimation can be available for patients with a limited range of whole body motion.



Figure 1. (left) Schematic representation of vertical reaching task. (right) End point transition. (a) only with PD feedback control (b) with tacit learning in addition to the PD control.



Figure 2. A reference anatomy (left) is automatically transferred to arbitrary humanoid characters. This is achieved by combining interpolated skin correspondences with anatomical rules.



Figure 3. After identifying the SESC parameter of the humanoid (Stanbot), it is possible to estimate the position of its CoM. SESC identification was performed with a reduced number of postures, to mimic a patient in need of additional support to maintain a standing pose.

Fig. 3 shows the identification results [27]. Even with a limited motion, it was possible to estimate the position of the simulated robot's CoM projected to onto the ground. This estimation errors are likely due to the lack of an exciting trajectory for identification. Nonetheless, if the postures used during identification describe a patient's range of motion, the CoM estimation can still be valuable.

6.1.4. Interface for identification of the Statically Equivalent Serial Chain's parameters and Balance Assessment

Participants: Alejandro González, Mitsuhiro Hayashibe, Philippe Fraisse.

CoM trajectory can be used to improve the current rehabilitation standards. After an identification phase, a personalized CoM estimate can be obtained using a SESC. Furthermore, using low-cost sensors (Kinect and Wii balance board), make the personalized estimate feasible inside a patient's home. This work focuses on the effect that a visual adaptive interface can have on the SESC identification phase. Specifically on improving its speed and quality. A study conducted on 6 subjects showed a faster convergence and a lower root mean square error (rmse) when the adaptive interface is applied. We find that for the same error (30 mm), the identification with the interface was performed in half the time (86 s) than the one without it (163 s). Similarly, for the same session length (120 s), rmse was of 24.5 mm using the interface and of 34.5 mm without it.

Additionally CoM dynamics may be used to determine stability. Fig. 4 shows an example of this during a squat task. The zero rate of angular momentum (ZRAM) can be used to determine the dynamic stability of a humanoid robot. It can be used to determine the position foot placement to avoid falls.

6.1.5. Forward Estimation of Joint Torque from EMG Signal through Muscle Synergy Combinations

Participants: Zhan Li, Mitsuhiro Hayashibe, David Guiraud.

We investigate the approaches of estimating the ankle joint torque from EMG/activations of associated muscle groups. The approaches discussed fall into two main categories: i) full utilization of both of extension and flexion EMG/activations for estimating the joint torque; ii) exploitation of muscle synergy extraction of EMG/activations and consequent usage of extracted components in reduced space for estimating the joint torque. Comparison is made between the two methods with experimental data of five able-bodied subjects. From the results we conclude that, method ii) with muscle synergy extraction may not degrade the performance of method i) but meanwhile show the muscle synergic ratios for generating the joint torque, and involvement of joint position and velocity information can improve the estimation for both methods.

6.1.6. Prediction of hand tremor through EMG-based fatigue tracking

Participants: Sourav Chandra, Mitsuhiro Hayashibe, Thondiyath Asokan [IITMadrass, India].

Laparoscopic surgical procedure is a very tiring procedure for a surgeon due to the specialized prolonged arm movement with a modular tool. Prolonged activity of arm muscle in such condition induces muscle fatigue which induces hand tremor. Hand tremor not only drastically affects positional accuracy; it also increases the collateral tissue damage. Nullification of this tremor has been the area of active research topic in surgical robotics for last few decades. Though Surface ElectroMyoGram (SEMG) has been used for modeling hand tremor of microsugeons, a single model for predicting amplitude and frequency of such tremor has not been investigated for laparoscopy so far. A model of muscle fatigue induced hand tremor in laparoscopic activity is necessary in order to nullify this hand tremor effect and increase positional accuracy. SEMG is a crucial biopotential in order to get the estimation of the muscle fatigue state. A positive correlation was found among SEMG and hand tremor in frequency domain as shown in Fig. 6 below. In this work, a model based prediction of fatigue induced hand tremor will be investigated with the vicinity of SEMG and other wearable inertial sensor data. The model is intended to have a dynamic structure, which can capture the complexity of the muscle fatigue state to some extent and its effect on the hand tremor amplitude and frequency.

6.1.7. Mobile gait analysis

Participants: Vincent Bonnet [M2H, UM1, Montpellier], Christine Azevedo Coste, Christian Geny [CHU Montpellier], Lionel Lapierre [LIRMM, Montpellier], René Zapata [LIRMM, Montpellier].



Figure 4. We show the trajectory of the zero rate of angular momentum (ZRAM) for a squat task. When the ZRAM is found inside the support polygon, the movement can be considered stable. Unstable movements (C-D) do not determine a fall. The subject may still recover using a balancing strategy; or by taking a step.



Figure 5. Normalized muscle synergy ratios of the five subjects, under isotonic situation with 10Nm plantar load and 5Nm dorsa load

The Video-Kinect-Bot, an affordable mobile platform for pathological gait analysis was developed to assess pathological spatio-temporal parameters. The system, driven by a Kinect sensor, is able to follow a patient at constant distance on his own defined path, and to estimate gait spatio-temporal parameters. Robust Tracking-Learning-Detection algorithm estimates the positions of targets attached to the trunk and heels of the patient. Real-condition experimental validation including corridor, occlusion cases, and illumination change was performed. A gold standard stereophotogrammetric system was also used and shown a good tracking of patient and an accuracy in stride length estimate of 2%.

The Empirical Mode Decomposition (EMD) method was evaluated to estimate the 3D orientation of the lower trunk during walking using the angular velocity signals generated by a wearable inertial measurement unit (IMU) and notably flawed by drift. The IMU was mounted on the lower trunk (L4-L5) with its active axes aligned with the relevant anatomical axes. The proposed method performs an offline analysis but has the advantage of not requiring any parameter tuning. The method was validated in two groups of 15 subjects, one during overground walking, with 180° turnings, and the other during treadmill walking, both for steady-state and transient speeds, using stereophotogrammetric data. Comparative analysis of the results showed that the IMU/EMD method is able to successfully detrend the integrated angular velocities and estimate lateral bending, flexion-extension as well as axial rotations of the lower trunk during walking with RMS errors of 1 deg for straight walking and lower than 2.5 deg for walking with turnings. This work was accepted for publication in Sensors journal for a special issue concerning wearable-sensor for gait analysis in 2014 with the following collaborators V. Bonnet, S. Ramdani, C. Azevedo-Coste, P. Fraisse, C. Mazzà and A. Cappozzo. Data relative to the pitch, roll and yaw angles obtained for one randomly selected treadmill walking trial. The integrated angular velocities (grey line) and the resulting trends (black line) are estimated using EMD (a) during all the trial; zoom over 20 s on the corresponding detrended angles are thereafter estimated (black line) and compared with those obtained using stereophotogrammetry (grey line).

This work is supported by a NOVARTIS funding (see Partnerships and Cooperations section).



Figure 6. Frequency domain correlation of sEMG and hand tremor during prolonged arm movement



Figure 7. (**Left:**) Detail of the Video-Kinect-Bot system and experimental setup (**Right:**) example of subject tracking in real-environment.

6.2. Function control and synthesis

6.2.1. Analysis of infection risk in surgery block

Participants: Christine Azevedo Coste, Roger Pissard Gibollet [SED Inria Grenoble Rhône-Alpes], Gabriel Birgand [Bichat Hospital, Paris], Jean-Christophe Lucet [Bichat Hospital, Paris], Gaëlle Toupet [Bichat Hospital, Paris].

Despite the increasing implementation of preventive measures, surgical-site infection still induces a substantial burden. Inappropriate staff behaviors can lead to environmental contamination in the operating room and subsequent surgical site infection. The present study focuses on the continued assessment of operating room staff behavior using a motion tracking system, and the evaluation of the impact of this behavior on the surgical-site infection risk during surgical procedures.

A multicenter observational study has been done in 2013, including 10 operating rooms of cardiac and orthopedic surgery in 12 healthcare facilities. A motion tracking system including 8 optical cameras (VICON-Bonita®) recorded movements of reflective markers placed on the surgical caps/hoods of each person entering the room. Different configurations of markers positioning were used to distinguish between staff category. Doors opening were observed as well by means of wireless inertial sensors fixed on the doors and synchronized with the motion tracking system. We have collected information on the operating room staff, surgical procedures and surgical environment characteristics ([2]).

Recorded data will be analyzed and staff behaviors will be assessed by the quantification of displacements within the operating room. Results will aim at bringing a rationale to the prevention of airborne microorganism transmission by the description of best behaviors rules in the operating room.

This protocol was approved by the Institutional Review Board of the (IRB) of Paris North Hospitals, Paris 7 University, AP-HP (n° 11-113, April 6 2012). The work is supported by Inria SENSBIO ADT and ARIBO Preqhos project.

6.2.2. Drop-foot correction in post-stroke hemiplegic patients

Participants: Christine Azevedo Coste, Roger Pissard-Gibollet [SED Inria Grenoble Rhône-Alpes], Jérôme Froger [Nîmes Hospital, Le Grau du Roi], Claire Delablachellerie [Nîmes Hospital, Le Grau du Roi].

Electrical stimulation has been proven to have orthotic and carryover effects on individuals with post-stroke hemiplegia with a foot drop syndrome. One of the drawbacks of the technique is the lack of adaptability to changes in gait (speed, type of floor, stairs, dorsiflexion quality etc). But, real-time modification of stimulation patterns is not feasible using gait event detection like proposed in all available stimulators. In the present study we investigate two questions: 1) is it possible to validate on individuals with foot drop an algorithm able to estimate online the continuous gait cycle phase from a unique wireless sensor placed on lower limbs and 2) is it possible to trig a drop foot stimulator based on events extracted from this phase information.

Methods : 20 subjects with post-stroke hemiplegia participated to the study. A wireless inertial measurement unit was placed on the unaffected leg of the subjects and was used to estimate the gait phase on a distant laptop. The subjects performed 3 trials in each of the 3 following conditions: **C1** no stimulation aid, **C2** electrical stimulation assistance triggered by heel switch **C3** electrical stimulation assistance wirelessly triggered based on the proposed algorithm.

Results : 1) the proposed algorithm was able to estimate online the continuous gait cycle phase, 2) events could be extracted from this phase information in order to trig an electrical stimulator using this algorithm instead of heel switch.

Conclusion : the online estimation of continuous gait cycle phase on individuals with stroke is possible. Events can be extracted from the phase information in order to trig a stimulator **C3** instead of using heel switch detection **C2**. The robustness of the proposed solution to gait modifications is intrinsically guaranteed by the use of automatic control theory. These results open promising applications using programmable stimulators which parameters could be modified online based on gait phase observation.

This protocol was approved by Nîmes Ethical Committee, AFSSAPS and CNIL. The work is supported by Inria SENSBIO ADT.

6.2.3. Freezing of Gait detection in Parkinsonian individuals

Participants: Christine Azevedo Coste, Christian Geny [CHU Montpellier], Maud Pasquier [Inria Grenoble Rhône-Alpes], Benoît Sijobert.

Parkinson's disease (PD) is the second most common neurodegenerative disorder. This chronic disease can lead to gait disturbances and falls inducing important reduction of the quality of life. One common symptom is the Freezing of Gait (FOG), an episodic inability to generate effective stepping in the absence of any known cause other than Parkinsonism. It can occur during initiation of the first step, turning, dual task, walking through narrow spaces, reaching destinations or passing through doorways. It is an episodic absence or marked reduction of forward progression of the feet despite the intention to walk. FOG are reported by the patient as a subjective feeling of "the feet being glued to the ground". Clinical evaluation of video recordings of patients by one to three observers is the gold standard to identify FOG events. The evaluation of clinical effects of the treatments would benefit from objective, standardized FOG measures. Moore et al. (2008;2013) have proposed a technique to identify FOG episodes based on the frequency properties of leg vertical accelerations (fig.9). The approach is based on the hypothesis that FOG occurrences are associated to trembling motion, which affect limb acceleration signal. They have introduced the so-called freeze index (FI): the ratio between the signal power in the trembling band (3 Hz - 8 Hz) and the signal power in the locomotor band (0.5 Hz-3 Hz). The FI method was validated using one to 7 accelerometers mounted on patients with satisfactory detection results. If many FOG episodes can be associated to festination (trampling) it is not the case for all of them. Therefore, we claim that all the FOG episodes cannot be detected by the FI method. In the present paper we propose a complementary index in order to take into account not only festination but also other freezing characteristics. Furthermore we intend to propose a solution based on a minimal number of embedded sensors and detection algorithms for future real-time applications.



*Figure 8. **System architecture.** Description of the system architecture used in the study. A sensor node (inertial measurement unit (IMU)) is placed on the unaffected side shank. Data is sent to the sink node of the laptop. Data is processed on the laptop and a gait phase is estimated. Depending on the phase value the stimulator is switched ON through its trigger node. An extra sensor node is also sending data to the sink node and data is saved for offline processing.*



Figure 9. Freezing of Gait observation using inertial sensors.

This work is supported by SENSBIO Inria ADT and DEMARPARK AOI (see Partnerships and Cooperations section).

6.2.4. *Effects of direct electrical stimulation of the brain during awake surgeries: towards improvements of the functional mapping*

Participants: François Bonnetblanc, David Guiraud, Marion Vincent, Mitsuhiro Hayashibe, Hugues Duffau [Neurosurgery department, CHU-Gui de Chauliac], Guillaume Herbet [Neurosurgery department, CHU-Gui de Chauliac], Benedicte Poulin-Charronnat [LEAD, Univ. Dijon].

« Awake surgery » consists in removing some infiltrative and slow-growing brain tumoral tissue in an awake patient. The neurosurgeon performs an anatomo-functional mapping of the brain by electrically stimulating brain areas near the tumor to discriminate functional vs. non functional areas. This stimulation is both made cortically and sub-cortically to preserve the functional connectivity. During the surgery itself, the patients are also involved by performing some tasks. Their recovery remains impressive with respect to the lesional volume. Despite the slow-growth of the lesion is invoked, these observations question our understanding of brain plasticity phenomena. Our multi-disciplinary approach aims to (i) better understand the effects of direct electrical stimulation of the brain to improve the functional mapping and also (ii) to build new functional assessments performed by the patient and based on new technologies applied to Health. By systematically performing these precise assessments before, after and during the surgery we hope to better understand brain functions, plasticity and dynamics in order to improve the surgical planning, functional mapping, rehabilitation procedures and quality of life of the patients.

6.2.5. *Translational research and stroke*

Participants: Anirban Dutta, David Guiraud.

Stroke is caused when an artery carrying blood from heart to an area in the brain bursts or a clot obstructs the blood flow thereby preventing delivery of oxygen and nutrients. About half of the stroke survivors are left with some degree of disability where the impairment of walking has been mentioned most frequently as the most important disability. There is, therefore, a pressing need to leverage insights from animal and human studies to address the complexity in clinical translation of rational multi-level electrotherapy protocols where the ability to customize such novel electrotherapy protocols has only recently become possible with advanced computational tools. Therefore the challenge is to develop advanced computational modeling tools at Inria, France, to design and customize innovative electrotherapy protocols to patient-specific needs, and then closely integrate them to drive (perhaps the first) individualized non-invasive electrotherapy program for clinical validation. The ongoing steps are i) Develop computational methods to identifying neural circuits related to the recovery from stroke [26], ii) Develop a computational method for online targeting of neural circuits and related pathways with non-invasive electrotherapy [21],[25], iii) Validate individualized multi-level non-invasive electrotherapy program with NIBS as an adjuvant treatment to NMES-assisted gait rehabilitation following stroke.

6.2.6. *Projet PERIMED*

Participants: Thomas Guiho, Christine Azevedo, Luc Bauchet, Charles Fattal, David Guiraud, Jean-Rodolphe Vignes.

Born in the 70's, Spinal cord stimulation is a general term including both peridural and intradural stimulation. Encouraged by Harkema's clinical result (in one paraplegic patient with step-like EMG activity) [43], several recent studies in rodents elicited locomotor synergies, bladder/bowel improvements and, in certain circumstances, restoration of supraspinal control after spinal cord injury [45]. Based on this previous work, our approach, mainly focused on bladder and bowel functions, aims both at asserting these discoveries in an intermediate model (pigs weighing between 50 and 60 kgs) and at providing further insight in spinal cord circuitries.

6.2.7. *Investigation of strategies for selective small nerve fiber stimulation in an animal model*

Participants: Paweł Maciejasz, Olivier Rossel, Christine Azevedo Coste, David Andreu, David Guiraud, Hubert Taillades [Institute of Biology, Montpellier].



Figure 10. Awake brain surgery and functional mapping.



Figure 11. Supraspinal cord stimulation .

The electrical stimulation of nerve fibers may allow to restore or augment some body functions lost due to disease or injury. However, in typical peripheral nerves there are thousands of nerve fibers with various diameters and functions. When standard rectangular pulses are used for nerve fiber stimulation, the big fibers are activated before smaller ones. However, for many clinical applications it would be beneficial if small fibers could be activated without activation of the big ones.

Already many stimulation techniques have been proposed for fiber type and diameter selective stimulation, e.g. analog block, slowly rising pulses, high frequency block. However, due to limited efficiency of those techniques, they are still not used in clinical practice. Based on the results of the computer simulations and the experiments performed previously in the earthworm model by our team, we have proposed some modification to the existing techniques, that may increase their efficiency.

In order to verify if the proposed modifications allow for increased selectivity of stimulation as compared to the techniques already proposed, a series of experiments in rabbit model has been scheduled. The experiment consists of two phases. The objective of the first one (3-6 rabbits), the preliminary one, is to determine an adequate method to evaluate the effects of stimulation, i.e. to find out a reliable method that would allow for discrimination between various types of fibers being activated by the stimulation. The objective of the second phase (5-15 rabbits), the exploratory one, is to compare and quantify the performance of various strategies for fiber type selective stimulation.

The experiments have been performed by the DEMAR team in rabbits in the Institute of Biology in Montpellier. During this experiment the sciatic nerve of the rabbit has been stimulated using tripolar nerve cuff electrode, whereas ENG and EMG signals, as well as ankle torque have been recorded. The experiments have been started in December 2012 and so far only the first phase of the study has been completed.

The experiment was authorized through the local ethics committee for animal experiment (authorization N° CEEA-LR-12084). The work is supported by INTENSE Project.

6.3. Neuroprostheses and technology

6.3.1. Abstraction and composition for formal design of neuroprostheses

Participants: Hélène Leroux, David Andreu, Karen Godary [LIRMM].

In the framework of specification and implementation of complex digital systems on FPGA, we have developed an approach based on components whose behavior and composition are specified by generalized interpreted T-time Petri nets. One of the inherent difficulties for designer is, on the behavioral part, to account for exceptions. This often leads to a complex modeling and is a source of human errors. Indeed, it is intricate to express all the possible situations (i.e. current state of model). We have defined a way to model exception handling by integrating the well-know concept of macroplace into the formalism. The analysability of the model and the efficiency of the implementation on FPGA (reactivity and surface, ie number of logic blocks) have been preserved. An example of macroplace is given in figure 13; it contains a sub-net (set of places of its refinement) from which exception handling is simply described by a dedicated output transition (transition t_e on fig. 13), whatever is the current state of the sub-net.

The new formalism has been defined, as well as the model transformation based equivalent PNML generation for using existing analysis tools.

Ongoing work deals with solving state evolution conflicts introducing priorities between transitions, to avoid reaching inconsistent global state while synchronously executing the model.

6.3.2. New FES dedicated digital processor for neurostimulator

Participants: David Andreu, David Guiraud.

We designed (patent pending) and prototyped a new neural FES dedicated processor and its associated (more compact and efficient) set of instructions, as well as an embedded sequencer for accurate timing in sequencing stimulations to be performed (by the stimulator). The new neural stimulator is based on a dedicated ASIC (Application Specific Integrated Circuit), that is able to drive up to 24 channels of stimulation in absolute synchronization, and with a programmable and controlled current level distribution (patent pending). This ASIC also allows for impedance measurement. The functions of the stimulator are currently implemented in two separate chips: an analog stimulation front-end (ASIC) and a field-programmable gate array (FPGA) embedding the logic control. The FPGA embeds the new FES dedicated processor setting the output stage configuration (poles configuration and current ratio between them) and running potentially complex stimulation profiles (with a 1 μ s time step and 5 μ A current step); example of generated stimulations are shown in Figure 12. It also embeds the protocol stack allowing for remote programming and online control. Online control relies on advanced and efficient modulation mechanisms, e.g. coefficient based modulation preserving balanced stimulation (Figure 12). And last but not least, it also embeds a monitoring module ensuring the respect of safety constraints stemming both from target tissue protection and electrode integrity preservation; this reference model based monitoring module ensures (configurable) current and quantity of injected charges limits and thus safe stimulation whatever are electrodes to be used (particularly for thin-film micro-electrodes). Safety limits must be defined by users (partners) according to the target and electrodes to be used.

6.3.3. Attitude reconstruction from IMU signals

Participants: Jonathan Peguet [IFMA], Daniel Simon, Christine Azevedo Coste, Roger Pissard-Gibollet [SED Inria Grenoble Rhône-Alpes].

Inertial Measurement Units (IMUs) are currently used by the team for real-time estimation of limbs attitude, e.g. as in section 6.2.2 where the attitude of a leg while walking feeds a gait phase estimator. The IMUs embedded in the FOX nodes (manufactured by HiKob) include 3 gyrometers, 3 accelerometers and 3 magnetometers, from which the attitude (e.g. Euler angles) of the node can be computed. The raw measurement signals can be either processed locally in the nodes, or sent on wireless links to be processed on a remote computer.

The raw signals issued from sensors are subject to noise and bias. Additionally, the raw data flow can be corrupted by timing disturbances induced by communication and computation. Hence, the attitude reconstruction filters must be robust against disturbances such as noise, bias, jitter and data loss. To evaluate the robustness of attitude reconstruction filters, a software simulation package dedicated to IMUs design and analysis has been customized from the Imusim package (initially developed in Python under GPL at Univ. of Edinburgh, U.K. [44]).

The Imusim modeling features include realistic IMUs models with noise and bias, calibration procedures, radio channels deficiencies and computing timing parameters. Several versions of Extended Kalman Filters and Non-Linear Observers, in particular those previously developed at Inria Grenoble Rhône-Alpes, have been integrated and successfully tested against measuring noise. The work is supported by Inria SENS BIO ADT.

6.3.4. Fast simulation of hybrid dynamical systems

Participants: Abir Ben Khaled [IFPEN], Daniel Simon, Mongi Ben Gaid [IFPEN].

When dealing with the design of complex systems, simulation is an indisputable step between concept design and prototype validation. Realistic simulations allow for the preliminary evaluation, tuning and possibly redesign of proposed solutions ahead of implementation, thus lowering the risks. However, the simulation of high-fidelity models is time consuming, and reaching real-time constraints is out of the capabilities of monolithic simulations running on single cores.

The aim of the on-going work is to speed up the numerical integration of hybrid dynamical systems, eventually until reaching a real-time execution, while keeping the integration errors inside controlled bounds. The basic approach consists in splitting the system into sub-models, which are integrated in parallel. It has been shown that an efficient partition must minimize the interactions between sub-models, in particular by confining



Figure 12. Examples of stimulations (observed at the output of the stimulator)

discontinuities processing inside each component. Automatic partitioning, based on some particular incidence matrices of the original system, has been investigated [17]. The method was tested with an automotive engine model, but it is generic and can be applied to other systems of hybrid ODEs/DAEs, as are large sets of muscular fibers.

6.3.5. ENG amplifier front-end

Participants: Mariam Abdallah, Fabien Soulier, Serge Bernard, Guy Cathébras.

Electroneurogram acquisition systems are usually based on tripolar cuff electrodes that are known to decrease noise from external sources, such as muscular fibers (EMG) or stimulation artifacts. Thus, we studied a preamplifier associated with this kind of electrode in a true-tripole configuration. It is designed at the transistor level to lower the number of transistors while still rejecting parasitical signals. This kind of integration reduces the size, power consumption and noise of the preamplifier compared to classical true-tripolar structures.



Figure 13. Classical structure of a true-tripolar ENG preamplifier.

The true-tripole configuration consists of linear combination of signals coming from the three poles

$$V_{out} = A \left(V_{in1} - \frac{V_{in2} + V_{in3}}{2} \right) \quad (1)$$

This combination is usually realized thanks to several differential amplifiers as shown in the figure 13 , whereas the proposed preamplifier is designed as a differential pair whose negative input transistor is split into only two smaller ones. (fig. 14). The circuit is based on a modified ASIC in AMS CMOS 0.35 μm technology, with 3.3 V supply. The preamplifier provides three functions which are:

- to combine the input signals as shown in the equation (1),
- to barely amplify the neural signal to an acceptable SNR,
- and to present a differential output to a variable-gain amplifier (not presented here, but integrated into the ASIC).



Figure 14. Three input preamplifier schematic.

To characterize the three-input preamplifier, we have to define three orthogonal modes, starting with the main mode expected to be amplified

$$V_{in1} = -2V_{in2} = -2V_{in3}, \quad (2)$$

the common mode, and the differential parasitic mode expected to be as low as possible to achieve a good EMG rejection:

$$V_{in1} = V_{in2} = V_{in3}, \quad (3)$$

$$V_{in1} = 0, \quad V_{in2} = -V_{in3}. \quad (4)$$

DC and AC simulations were performed for these three modes. The results are presented in the figure 15 . The main results of these simulations are:

- more than 150 dB rejection ratio for the common and differential modes compared to main one,
- dynamic range of about 5 mV,
- 200 kHz bandwidth (that is far above the needs for ENG acquisition),
- the estimated flicker noise due to input and load transistors is below the μV on the required bandwidth.

This work has been presented to the 18th IFESS Annual Conference [16].

6.3.6. Characterization of the CAFE12 chip

Participants: Jérémie Salles, Fabien Soulier, Serge Bernard, Guy Cathébras.



Figure 15. DC (on the left) and AC (on the right) simulation results for main (b), common (a) and differential modes (c). AC differential mode is too low to be simulated using typical values.

The circuit CAFE12 (Cool Analog Front End, 12 poles) used in StimND, which was designed in 2006, exploit the bases of a DEMAR patent. A characterization of a circuit (1st version, manufactured in 2006-2007) showed limitations to its capabilities. Thus a 2nd version was designed and manufactured in 2012 to improve the circuit linearity and consumption. CAFE12 is an ASIC generating 12 current outputs. This ASIC was developed in high voltage CMOS technology (H35, Austria Mikro Systems). Each output is able to deliver/absorb a current as high as 5mA.

The measurements presented below were carried on 3 CAFE12_V2 prototypes (C8002 & C8003). Some comparisons with 2 CAFE12_V1 (T1201 & nD09) prototypes are also shown.

- Integral non linearity (INL) Figure 16 highlights the INL improvement of the anodic generators. This significant decrease is due to a wiring modification on a specific operational amplifier (OPA). No improvement on the cathodic side was expected.
- Differential non linearity (DNL) The noticed improvement on the INL is also noticeable on the differential non linearity on both anodic and cathodic sides (Figure 17 and Figure 18).

The following table 1 sums up the characterization results. The main achievements are better anodic generators (linearity and gain) and a reduced static consumption.

Table 1.

	INL (LSB)		DNL (LSB)		Gain accuracy (%)		Power (mW)
	Anode	Cathode	Anode	Cathode	Anode	Cathode	Total
CAFE12_V1	-26 to 4	±5	±0.02	±0.015	±13.43	±6.19	50
CAFE12_V2	-6 to 2	-4 to 6	±0.01	±0.01	±6.53	±5.90	38



Figure 16. INL comparison, anodic generators (CAFE12_V1 & CAFE12_V2)



Figure 17. DNL comparison, anodic side (CAFE12_V1 & CAFE12_V2)

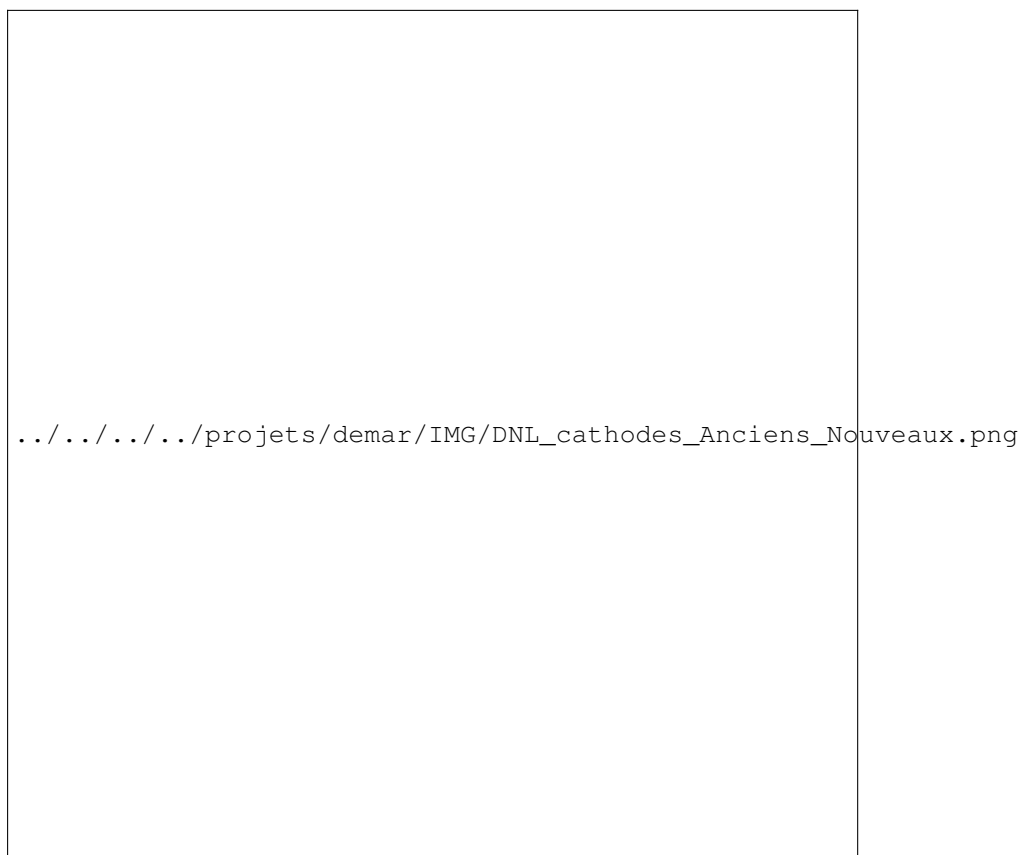


Figure 18. DNL comparison, cathodic side (CAFE12_V1 & CAFE12_V2)

MODEMIC Project-Team

6. New Results

6.1. Macroscopic models

6.1.1. About species coexistence

Participants: Fabien Campillo, Jérôme Harmand, Claude Lobry, Alain Rapaport, Tewfik Sari.

The so called “Principle of Competitive Exclusion” states that in the chemostat model, in presence of p substrates only p species can coexist. By contrast, in a bioreactor used for decontamination, hundreds to thousand different species are observed in presence of just very few substrates. Actually the classical chemostat models rely on assumptions: perfect mixing, substrate-dependent growth rate, constant environment, only asymptotic results are considered, deterministic continuous models...

A long term objective since Mere Inria project-team is to revisit the chemostat model in the absence of one or more of these hypotheses having in view the question of coexistence. In our “major publications” we proved coexistence in absence of the second hypothesis [6] or during long transient [9]. In [57], we consider the case where the environment (in some sense) is periodic in time. Our results concerning non continuous and/or stochastic models (see Section 6.2.3) are also a first step in avoiding the fifth hypothesis.

6.1.2. Modeling and analysis of bioprocesses

Participants: Boumédiène Benyahia, Radhouane Fekih-Salem, Jérôme Harmand, Claude Lobry, Guilherme Pimentel, Alain Rapaport, Tewfik Sari.

Within the supervision of the PhD thesis of R. Fekih-Salem, we have studied a chemostat model where the species are present in two forms, isolated and aggregated individuals, such as attached bacteria in biofilm or bacteria in flocks [22]. We show that our general model contains a lot of models that were previously considered in the literature [77]. Assuming that flocculation and deflocculation dynamics are fast compared to the growth of the species, we construct and analyse a reduced chemostat-like model in which both the growth functions and the apparent dilution rate depend on the density of the species.

Within the framework of the PhD thesis of B. Benyahia, we have included the fouling dynamics of membranes into the AM2 (or AMOCO) model and we have analyzed the resulting model (called the AM2b) [15]. In particular, we have integrated into this model the production and the degradation of Soluble Microbial Products (SMP), which are known to play an important role in the membrane fouling phenomenon. We show that under some general assumptions, the AM2b model has the same number of equilibria as the AM2 model and can exhibit bi-stability. However, under certain operating conditions or if biological parameters values are slightly modified, the AM2b model exhibits equilibria bifurcations and multi-stability properties.

The available anaerobic digestion models used for control purposes do usually only consider soluble matter. In fact, part of the pollutants are not soluble but are under a particulate form. In order to establish whether adding the dynamics of such matter into the models is important for the system behavior or not, we have studied new anaerobic models and established that depending on the kinetics of this additional reaction step, the qualitative behavior of the process may be significantly modified [44].

This year, G. Pimentel as started a PhD co-supervised with the University of Mons, about modeling of the membrane fouling in bioreactors in view of control. The objective is to represent cake formation and air cross-flow as a manipulated variable in the models, in view of future studies of control strategies for improving the efficiency of MBR processes [35], [47], [52], [53].

6.1.3. Ecosystem functioning in heterogeneous environments

Participants: Céline Casenave, Jérôme Harmand, Alain Rapaport.

This year, we have carried out a study of particular spatial interconnections such as “buffered” configurations, and its ecological impacts in terms of setup of a species in environments that are unfavorable when perfectly mixed. We have extended our previous results about the design of configurations for obtaining a global stability [28]. New conditions have been obtained for a species to setup when it is impossible in a perfectly mixed environment. At the opposite, we have characterized configurations that could destabilize bioprocesses.

With UMR Géosciences (Univ. of Rennes 1), we have carried on our analysis of the equivalence of two soil fracture models in terms of transfer functions [19]: the MINC (Multiple INTERactionng Continua) and MRMT (Multiple Rate Mass Transfer) models that are quite popular in soil hydrodynamics. We have shown that a strict equivalence can be obtained if one considers different volumes in the discretization of the MINC model. For the moment, this study concerns the transfer of abiotic substances only.

In soil ecosystems, it often happens that several functional groups can be detected to operate concomitantly. We have investigated the mathematical properties of a relatively simple model that has been proposed by the UREP lab (Inra Clermont), that distinguishes explicitly two functional groups of micro-organisms: the decomposers of SOM (soil organic mater) and the producers of SOM, and compared it with a single microbial compartment model in terms of prediction of the so-called “priming effect” [27].

Together with agronomists of the UMR Eco & Sols (Cirad, Inra, IRD, Montpellier SupAgro) and the supervision of the MSc thesis of C. Droin, we have proposed and started to study a new model of consumer/resource for soil microbial ecosystems, in which we explicitly distinguish available and recalcitrant resources [71].

6.2. Stochastic and hybrid models

6.2.1. Stochastic macroscopic models

Participants: Fabien Campillo, Marc Joannides.

We continued our study of stochastic modeling of the chemostat. In a first study we establish the Fokker-Planck equation of the law of the diffusion process. This equation features relevant boundary condition for the washout. We propose specific finite difference schemes to account for this feature [18]. In a second work we adopt the same approach to more accurately study the logistic model [64] which allowed us to propose estimation procedures to take into account the extinction (see Section 6.3.2).

6.2.2. From microscopic models to macroscopic laws

Participants: Fabien Campillo, Coralie Fritsch, Jérôme Harmand, Claude Lobry.

We proposed a chemostat model where the bacterial population is individually-based (IBM), each bacterium is explicitly represented and has a mass evolving continuously over time, and where the substrate concentration is represented as a conventional ordinary differential equation. These two components are coupled with the bacterial consumption. Mechanisms acting on the bacteria are explicitly described (growth, division and uptake). Bacteria interact via consumption. We set the exact Monte Carlo simulation algorithm of this model and its mathematical representation as a stochastic process. We prove the convergence of this process to the solution of an integro-differential equation (IDE) when the population size tends to infinity. The IDE is discretized with the help of finite differences, with simulation as well as the IBM are developed in Python with the help of the Gamma-Team (UMR Mistea) [63].

Finally with O. Ovaskainen (Univ. of Helsinki) we developed an evolution model for the chemostat.

6.2.3. Simulation and analysis of hybrid models and the atto-fox problem

Participants: Fabien Campillo, Claude Lobry, Alain Rapaport.

We proposed a new “hybrid” model for the simulation of biofilm growth in a plug flow bioreactor, that combines information from three scales: a microscopic one for the individual bacteria, a mesoscopic or “coarse-grained” one that homogenizes at an intermediate scale the quantities relevant to the attachment/detachment process, and a macroscopic one in terms of substrate concentration. In contrast to existing partial differential equations models, this approach is based on a description of biological mechanisms at the individual scale, thus bringing in a biological justification of the attachment/detachment process responsible for the macroscopic behavior [20].

We pursue our study of the “atto-fox” question in the classical Rosenzweig-MacArthur model for a resource-consumer relationship: for certain values of parameters the system has a limit cycle such that the smallest value reached by the resource on this cycle is so small that the model validity is jeopardized [65].

6.3. Identification and control

6.3.1. Reconstruction methods of kinetics functions

Participant: Alain Rapaport.

A collaboration with Sisyphé Inria project-team has led to the development of a new identification method of the kinetics function in the chemostat model, without any a priori on the monotonicity of the function (thus allowing the consideration of bio-processes that are unstable in open loop) [29]. An extension of this method, that is based on singular perturbations, has been proposed for the extremum seeking problem with only two times scale (instead of three for the usual extremum seeking techniques [75]) [50].

6.3.2. Parameter estimation and particle filtering

Participants: Amine Boutoub, Fabien Campillo, Jérôme Harmand, Marc Joannides.

We consider a stochastic logistic growth model involving both birth and death rates in the drift and diffusion coefficients for which extinction eventually occurs almost surely. We then use the numerical integration of the Fokker-Planck equation presented in Section 6.2.1 to build a likelihood function for the unknown model parameters, when discretely sampled data is available. The existing estimation methods need adaptation in order to deal with the extinction problem. We propose such adaptations, based on the particular form of the Fokker-Planck equation, and we evaluate their performances with numerical simulations [64].

We develop particle approximation methods for the nonlinear filtering and parameter estimation with the help of the chemostat model [70].

6.3.3. Functional assignments methods

Participants: Jérôme Harmand, Alain Rapaport.

Following the philosophy of the work that was achieved within the framework of the former PhD thesis of M. Dumont [3], we have applied part of the proposed methodology for a better understanding of the dynamics of specific species of the anaerobic digestion [30], with Chilean collaborators (see Sections 7.4.1.1 and 7.4.2).

Using a combinatorial approach, we have also developed together with UMR Eco & Sols (Cirad, Inra, IRD, SupAgro – Montpellier) a new method to study the role of the interactions within bacterial species on the performance of an ecosystem. More precisely, based on the specific characteristics of the species of a community and the way they interact between each other, we propose a method to predict the behavior of the ecosystem with respect to its biodiversity [34], [25].

6.3.4. Stabilizing strategies for bioprocesses

Participants: Céline Casenave, Jérôme Harmand, Guilherme Pimentel, Alain Rapaport.

We have carrying on developments of stabilizing strategies for bio-processes, with specific characteristics:

- In [48], it has been shown how the buffered configuration of two chemostat models studied in Section 6.1.3 provides an efficient way to stabilize bioprocesses with inhibition. In the same spirit, it has been shown how the consideration of a “passive” buffer (i.e. without biological reaction) can play the role of a delay and enlarge the attraction basin of stable equilibria [49].
- It often happens in bio-processes that measurements are delayed. In [46], a new stabilizing strategy have been proposed to robustly cope with such delays for single chemostats with inhibition.
- For the stabilization of a series of reactors with multiple inputs, a control strategy based on a linearizing control law coupled with a state observer and an anti windup component has been proposed [66], [67], in view of its application in wine fermentation processes. The originality and difficulty of this multi-inputs problem are due to the inputs constraint that imposes that the manipulated dilution rate of each tank has to be less or equal than the one of the previous tank.

6.3.5. Optimal syntheses for bioprocesses control

Participants: T erence Bayen, Amel Ghouali, J er me Harmand, Claude Lobry, Alain Rapaport, Tewfik Sari.

We have continued our activities related to the development of optimal control laws for the optimization of bio-processes, notably in taking advantage of the presence of T. Bayen in the team in 2013. Three kinds of results, depending on the kind of processes under interest, were obtained.

a. Control of batch processes. Sequencing Batch bioReactors can be used to efficiently treat water containing both carbonaceous and nitrogenous pollutants. In such a case, an efficient control that can be used is the oxygen concentration. In such systems, oxic and anoxic bacterial are in competition for certain substances. For a simplified version of this complex situation, we have investigated the optimal strategies in order to minimize the energy to be introduced into the system under performance constraints. The originality of the approach lies in the fact that the original problem is transformed into a very general form. Thus, the optimal control problem is formulated and solved for a very general class of systems of ecological relevance [16].

b. Control of fed-batch processes. References [13], [36], [60] are devoted to the study of a bioreactor which is operated in fed-batch mode. We aim at finding an optimal control in feedback form (i.e. depending of the state) that steers the system in a minimal amount of time to a target (which typically has several interests in wastewater treatment). Finding an optimal control in feedback form is crucial from a practical point of view. In [13], previous works on the subject are extended to the case where the growth function depends on an additional product of the reaction. In the references [36], [60], we provide an optimal control in feedback form whenever mortality and recycling rates are considered, and in the case where the maximum dilution rate is not large enough to compete the growth of the species (in the latter case, this implies that the singular arc is non-necessary controllable implying difficulties in determining optimal controls). References [58], [61] are devoted to the study of optimal control problem governed by a chemostat-type model. In [58], an optimal feedback control law is provided in order to optimize the selection of a species in a chemostat model with one limiting substrate and two species. This brings an interesting issue in order to extend this result to the case where the number of species is larger than 3.

c. Coupled dynamics. References [59], [60] give the results of the study of an optimal control problem of a system coupling a culture of micro-algae limited by light and an anaerobic digester. The mathematical model for the dynamics of the reactors takes into account a periodic day-night model of the light in the culture of micro-algae and a chemostat model for the digester. Our aim is to optimize the production of methane in the digester during a certain number of days with respect to the dilution rate. In [59], some preliminary results on this problem are given for an optimal control problem governed by a one-dimensional Kolmogorov equation. In [60], the full system is analyzed by combining direct methods and indirect methods based on Pontryagin's Principle. In [62], we provide a complete characterization of optimal controls for a minimal time control problem where the system describes a two tanks gradostat model under a cascade inputs constraint. This model allows to create a gradient of resources that is expected to be more realistic to mimic real environment for studying micro-organisms growth.

6.4. Distributed delay systems

Participant: C eline Casenave.

In microbial ecosystems, time delays are often present. For a long time (especially with V. Volterra), distributed delay models (or integro-differential equations) have been proposed to take into account these delays in population models. Some dynamic problems dealing with integro-differential models can be tackled in an original way by using the methodology called "diffusive representation". Some works, which began during the PhD thesis of C eline Casenave, are still under development.

In [26], a new formulation of an integro-differential model of a porous media is proposed, based on this methodology. From this formulation, the dissipative and passive features of the porous wall are established, and numerical simulations are performed. A reduced order model is also proposed which summarizes the boundary behavior of the porous wall (⁵).

This work is done in collaboration with LAAS (Univ. Toulouse III) and the Gipsa-lab (CNRS, Grenoble-INP, Univ. Joseph Fourier, Univ. Stendhal). In the future, these works could be adapted to the case of microbial ecosystems.

6.5. Applications to wastewater treatment

Participants: Térence Bayen, Fabien Campillo, Radhouane Fekih-Salem, Amel Ghouali, Jérôme Harmand, Claude Lobry, Alain Rapaport, Tewfik Sari.

If an important part of our work has been done with the final objective of confronting models to data, the studies realized this year are rather theoretical (cf. research achieved within the framework of PhD theses by B. Benyahia, R. Fekih Salem, S. Hassam and G. Araujo Pimentel). In fact, they can be considered as prerequisites before being applied to real systems which, as for most Anaerobic MBRs, are still often found only at pilot scale and not yet applied on real sites.

Concerning the study of membrane fouling, we collaborate with our colleagues of the University Montpellier 2 within the framework of A. Charfi to characterize membrane fouling [43], [54], [42].

In association with the “Laboratoire d’Automatique de Tlemcen” (Univ. Aboubekr Belkaid) and the Gamma Team (UMR Mistea), Modemic launch the NuWat project (Numerics for water treatment research) in the Lirima network (see Section 7.4.2). The first visit of colleagues from the LAT allowed to make choices on the establishment of teachings for the Master in Tlemcen of general trainings and to define research priorities.

The collaboration with Moise Inria project-team has led to a patent application about an algorithm for “intelligent” pumps for the efficient treatment of large water resources [69]. The method relies on an extension of a former work [4] coupled with faithful simulations of the hydrodynamics of the resource and the pollutant dispersion. This typically applied for Chilean lakes, an application that we plan to launch within a common project with CIRIC Inria-Chile.

6.6. Applications to environmental microbiology

Participants: Céline Casenave, Jérôme Harmand, Alain Rapaport.

We have several ongoing works on the modeling of soil microbial ecosystems. The main characteristics of the models we develop with these partners, compared to aquatic microbial ecosystems, concern the availability of the resources, in terms of:

- spatial distribution and transfer of resources, using simple space representations, with the UMR Eco & Sols (Cirad, Inra, IRD, SupAgro – Montpellier) and the UMR Géosciences (Rennes). See Section 6.1.3 and references [28], [19];
- consideration of recalcitrant forms and recycling of nutrients, with UMR Eco & Sols (Cirad, Inra, IRD, SupAgro – Montpellier) and Inra UREP (Clermont). See Section 6.1.3 and [27], [71].

We have also proposed, together with the UMR Eco & Sols (Cirad, Inra, IRD, SupAgro – Montpellier), a new methodology to deduce from the observation of the performances of several assembling of reconstituted ecosystems, the number and the nature of species interactions (see Section 6.3.3 and [34], [25]).

The organization of a “research school” dedicated to the biologists of the marine research station of Banyuls (see Section 8.1) has led to a primary work about variable yield in marine microbial populations.

6.7. Applications to wine fermentation

Participants: Térence Bayen, Céline Casenave, Jérôme Harmand, Alain Rapaport.

⁵Two journal articles dealing with the identification of integro-differential models, and the controllability of some SISO Volterra models are still under revision.

We study the problem of the control of a Multi-State Continuous Fermentor (MSCF) composed of 4 reactors connected in series (the experimental pilot plant is located at Montpellier, in the UMR SPO (INRA, Montpellier SupAgro, Univ. Montpellier 1)). The goal is to control the sugar concentration of the four reactors with, as control inputs, the input flow rates of the four reactors. The originality of the problem comes from the cascade structure of the device which leads to a constraint on the control inputs. Two control strategies have been studied.

An output stabilizing control strategy. The linearizing control law proposed in [66], [67] (see Section 6.3.4) has been validated on numerical simulations, and then has been implemented (Labview-Matlab interface) on the experimental process. The obtained results are convincing; others experiments are scheduled in 2014 to refine the control law.

A minimal time state feedback strategy. The optimal state feedback studied in [62] (see Section 6.3.5) is of completely different nature, as it relies on bang-bang controls and singular arcs. We plan to couple this control law when far from the target with the previous stabilizing law when close from the target, in order to provide a practical sub-optimal strategy.

The first part of this work was conducted as a part of the European CAFE project (Computer-Aided Food processes for control Engineering) described in Section 7.3.1, in collaboration with CESAME (Univ. Catholique de Louvain-la-neuve), and UMR SPO.

A new project, see Section 7.2, in which the UMR SPO and the Unit Mistea are involved has begun in 2013. Preliminary work has been performed during the MSc thesis of S. Sekkat [74] about the modeling of the fermentation with addition of nitrogen in the MSCF.

6.8. Applications to micro-algae

Participants: T erence Bayen, Matthieu Sebbah.

An originality developed within the Biocore Inria project-team is to couple a bioreactor that cultivate micro-algae with an anaerobic digester, that uses micro-algae as a substrate that is then converted into valuable bio-gaz (methane). As micro-algae are micro-organisms whose growth is limited by light, one has to take into account periodic day-night model of the light. In [59], [61], control laws that maximize the biogaz production in this periodic framework have been proposed (see Section 6.3.5). In the framework of the Inria Project Lab "Algae in Silico" (see Section 7.2) and the Inria-CIRIC Center in Chile (see Section 7.4), several extensions and collaborations with Biocore Inria project-team are scheduled for the coming year.

6.9. Other results

This section contains some theoretical as well as applied results, that are not directly connected to the main field of the team.

Theoretical ecology

Participant: Tewfik Sari.

In [24], ecological trade-offs between species are studied to explain species coexistence in ecological communities. In our model, plant species compete for sites where each site has a fixed stress condition. Species differ both in stress tolerance and competitive ability. We derive the deterministic discrete-time dynamical system for the species abundances. We prove the conditions under which plant species can coexist in a stable equilibrium. We compare our model with a recently proposed, continuous-time dynamical system for a tolerance-fecundity trade-off in plant communities, and we show that this model is a special case of the continuous-time version of our model.

Calculus of variations

Participant: T erence Bayen.

The work [37] is devoted to the study of necessary and sufficient optimality conditions for weak and strong minima for optimal control problems governed by semi-linear parabolic equations; whereas in the field of calculus of variation, these conditions (such as Euler-Lagrange equation, Legendre's condition, Weierstrass's condition) have been deeply investigated, the study of strong solutions for optimal control problems of partial differential equations is new.

Ice cream crystallization

Participant: Céline Casenave.

We study the problem of the control of an ice cream crystallization process (the experimental pilot plant is located at Irstea Antony). The goal is to control the viscosity of the ice cream at the outlet of the continuous crystallizer. The problem has been studied in two steps.

Modeling, model reduction and parameter identification. On the basis of a population balance equation describing the evolution of the crystal size distribution (CSD) of the ice cream, and an energy balance equation, we have proposed an input-output reduced order model of the process, which is based on physical assumptions. The parameters of the model have been identified and the model has been validated from experimental data [68].

Design of the control law. Based on the reduced order model, a nonlinear control strategy based on an adaptive linearizing control law coupled with a Smith predictor to account for the measurement delay has been proposed [41], [66], [67]. The control has been implemented (Labview-Matlab interface) and then validated on the experimental pilot plant. During the industrial conference which has been organized in February 2013 by the European CAFE project (see Section 7.3.1), and which representatives of several industries in food processing attended, a live demonstration of the designed control law has been performed.

This work was conducted as a part of the European CAFE project, described in Section 7.3.1, in collaboration with CESAME (Univ. Catholique de Louvain-la-neuve), Irstea Antony and AgroParisTech.

Semi-Markov land use dynamic

Participant: Fabien Campillo, Angelo Raheiririna.

We pursued the development of semi-Markov model for the inference of land use dynamic from data proposed by IRD. The thesis of A. Raheiririna was defended in August 2013 [12]. Later in the year during the stay of A. Raheiririna in Montpellier we completed an article accepted by the journal ARIMA and that will be published in 2014 [17].

MORPHEME Project-Team

4. New Results

4.1. 3D reconstruction in fluorescence imaging

Participants: Emmanuel Soubies, Laure Blanc-Féraud, Sébastien Schaub.

This work was made in collaboration with Gilles Aubert, Laboratoire J.A. Dieudonné (CNRS, UNS).

We propose a new model for the reconstruction of biological structures using Multiple-Angle Total Internal Reflection Fluorescence Microscopy (MA-TIRFM). This recent microscopy technique allows the visualization of sub-cellular structures around the plasma membrane which is of fundamental importance in the comprehension of exchanges mechanisms of the cell. We present a 3D reconstruction method based on a shape prior information on the observed structures and robust to shot noise and background fluorescence. A novelty with respect to the state of the art is to propose a method allowing the recovery of multiple objects aligned along the axial axis.

TIRFM principle is based on the total internal reflection phenomenon of a light beam at the interface between two mediums of refractive indices n_i (incident) and n_t (transmitted) which produces an evanescent wave capable of exciting fluorophores that are near the coverslip surface. Excited fluorophores emit photons that are then collected by a CCD camera to produce a resulting 2D image (radial dimension). The 2D image formation is formulated as follows [29]:

$$S(x, y, \alpha) = I_0(\alpha) \int_0^\infty R(x, y, z) \exp\left(-\frac{z}{d(\alpha, \lambda)}\right) dz \quad (5)$$

where $S(x, y, \alpha)$ is the recorded image for the incident angle α , $R(x, y, z)$ denote the 3D unknown fluorophore density, $I_0(\alpha)$ is the intensity at the interface $d(\alpha, \lambda)$ is the penetration depth (theoretically known) and λ is the incident light wavelength. The problem is then to determine R in (1) from acquisitions S_α with different incident angles.

In order to solve this ill-posed inverse problem, we model the 3D unknown fluorophore density by a collection of parametrized objects defined on a state space $\mathcal{X} = P \times M$ by their location $\rho \in P$ and their marks (i.e. geometric attributes $\omega \in M$). The optimization problem can be formulated as a minimization problem where both the number of objects in the model and their parameters have to be estimated. This difficult combinatorial optimization problem is tackled by using a Marked Point Process approach [36] which allows modelling interactions between the objects in order to regularize the inverse problem.

Figure 1 right shows the Root Mean Square Errors (RMSE) of each estimated parameter for different noise levels on simulated data. We obtain a high accuracy reconstruction with an RMSE less than 10 nm for the radial position (x,y) and the radius. A larger RMSE (between 80 and 125 nm, depending on the noise level) is found on the axial position vesicles estimation. As we can see on figure 1 left, the error on the axial position estimation is due to the deepest objects (> 300 nm), objects close to the glass interface are well estimated. Figure 1 right shows also the robustness of the model with respect to shot noise and background fluorescence since the errors remain almost constant with the increasing noise level. The proposed method have also been tested on a real sample of beads of known diameters in order to quantify the quality of the reconstruction. The obtained results are promising for feature estimation of predefined shape structures [17].

4.2. Depth-variant blind restoration for confocal microscopy

Participants: Saima Ben Hadj, Laure Blanc-Féraud.

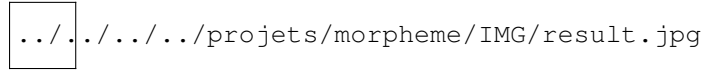


Figure 1. Left : Reconstructions for different noise levels (colors represent z positions of objects). (a) Simulated sample, (b) \rightarrow (c) \rightarrow (d) : Reconstruction for an increasing level of noise. Right : RMSE for different noise levels.

3D images of confocal microscopy basically suffer from two types of distortions: a depth-variant (DV) blur due to the variation of the refractive index between the different mediums composing the system and the imaged specimen, and a Poisson noise due to photon counting process at the sensor.

The Point Spread Function (PSF) is depth-variant and its knowledge is crucial for the restoration of these images. Nevertheless, the PSF is inaccessible in practice since it depends on the optical characteristics of the biological specimen and thus needs to be estimated for each different specimen.

In our previous work [5], [4], we developed a method for the joint estimation of the specimen function (the sharp and clean image) and the 3D DV PSF by minimizing a criterion arising from the maximum a posteriori approach. The DV PSF is approximated by a convex combination of a set of space-invariant PSFs taken at different depths.

Recently, we proposed to consider additional constraints on the PSF coming from the optical system modeling [21], [6]. In fact, the confocal microscopy PSF is related to the magnitude of a complex function known as *complex valued-amplitude PSF* whose shape and support are given in the Fourier domain by the numerical aperture of the optical system [30], [35]. This latter is known as it is given by the system manufacturer. We incorporate this constraint in the joint PSF and image estimation algorithm [5] by using the Gerchberg-Saxton algorithm (GS) [31] since it allows to alternate constraints in the spatial and frequency domains. Numerical tests on a simulated image of a bead shell are encouraging (cf. figures 2 (a), (b), (c), and (d) presenting z -slices of the original image, simulated and reconstructed images). In particular, the added constraint allows to better estimate the PSF shape compared to the previous method [5] (cf. figures 2 (e), (f), and (g)).

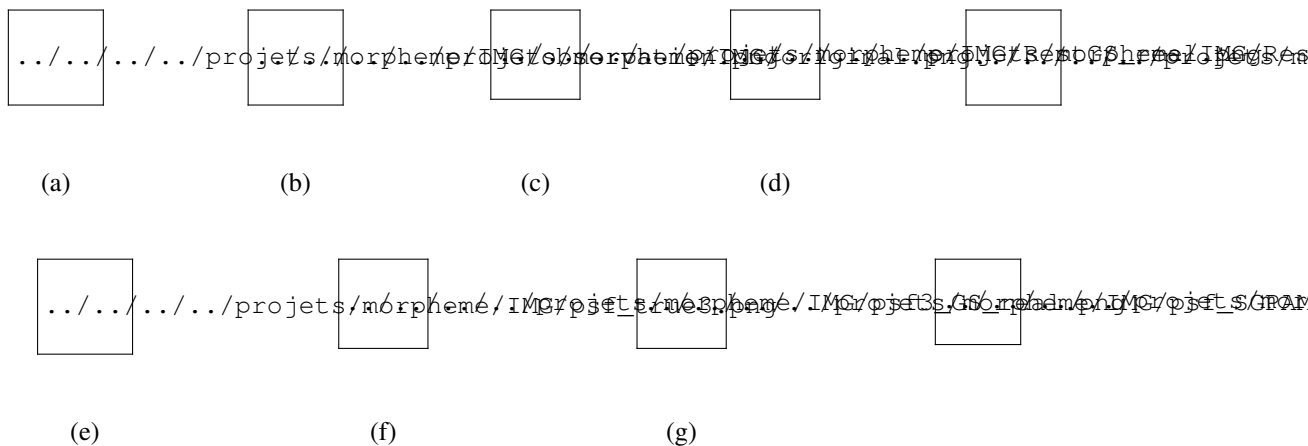


Figure 2. (Y , Z) slices of the simulated observation (a), true image (b) and PSF (e), estimated image (c) and PSF (f) with the additional PSF constraints, estimated image (d) and PSF (g) without the additional PSF constraints.

4.3. Head Tracking and Flagellum Tracing for Sperm Motility Analysis

Participants: Huei Fang Yang, Xavier Descombes, Grégoire Malandain, Sylvain Prigent.

This work is supported in part by ANR MOTIMO project.

Sperm quality assessment plays an important role in human fertility and animal breeding. One of the most important attributes for evaluating semen quality is sperm motility, according to the World Health Organization (WHO) report. When performed manually, semen analysis based on sperm motility is labor-intensive and subject to intra- and inter-observer variability. Computer-assisted sperm analysis (CASA) systems, in contrast, provide rapid and objective semen fertility assessment. In addition, they also offer a means of statistical analysis that may not be achieved by visual assessment. Hence, automated sperm motility analysis systems are highly desirable.

We present a computational framework designed to track the heads and trace the tails for quantitative analysis of sperm motility, which is illustrated in Figure 3. Our framework includes 3 modules: head detection, head registration, and flagellum tracing. These modules are performed sequentially to obtain the head trajectories and flagellar beat patterns. First, the head detection module detects the sperm heads in the first image of the image data using a Multiple Birth and Cut (MBC) algorithm. The detections are the inputs to the head registration module for obtaining the head trajectories and angles of head rotation. We use a block matching method to register the heads in the subsequent images with respect to the positions and angles of those detected in the first image. This is different from other tracking methods that consider only the head positions. Finally, we propose a flagellum tracing algorithm, based on a Markov chain Monte Carlo (MCMC) sampling method, to obtain the flagellar beat patterns.

We validate our framework using two microscopy image sequences of ram semen samples that were imaged at two different conditions, at which the sperms behave differently. The results show the effectiveness of our framework [19].

4.4. Tree-like Shapes Distance Using the Elastic Shape Analysis Framework

Participants: Alejandro Mottini, Xavier Descombes, Florence Besse.

The analysis and comparison of tree-like shapes is of great importance since many structures in nature can be described by them. In the field of biomedical imaging, trees have been used to describe structures such as neurons, blood vessels and lung airways. Since it is known that axon morphology provides information on their functioning and allows the characterization of pathological states, it is of paramount importance to develop methods to analyze their shape and to quantify differences in structures

We have developed a new method for comparing tree-like shapes that takes into account both topological and geometrical information [14], [15]. Our metric combines the Elastic Shape Analysis Framework originally designed for comparing shapes of 3D closed curves in Euclidean spaces with a matching process between branches. Moreover, the method is able to compute the mean shape of a population of trees.

As a first application, we used our method for the comparison of axon morphology. The performance was tested on a group of 61 (20 normal, 24 type one mutant and 17 type two mutant) 3D images, each containing one axonal tree. We have calculated inter and intra class distances between them and implemented a classification scheme. We have compared our results with the ones obtained by three other methods. Results showed that the proposed method better distinguishes between the two populations than the other methods.

4.5. 3D Modeling of developing organisms

Participants: Gaël Michelin, Grégoire Malandain, Léo Guignard [Virtual Plants], Christophe Godin [Virtual Plants].

This work is made in collaboration with Patrick Lemaire (CRBM).

Image-based studies of developing organs or embryos produce a huge quantity of data. To handle such high-throughput experimental protocols, automated computer-assisted methods are highly desirable. We aim at designing an efficient cell segmentation method from microscopic images. Similar to another work [32], the proposed approach is twofold: first, cell membranes are enhanced or extracted by the means of structure-based filters, and then perceptual grouping (i.e. tensor voting) allows to correct for segmentation gaps (see figure 6). We assessed different structure-based filters as well as different perceptual grouping strategies to identify the most efficient combination, in term of result quality and computational cost [13].



Figure 3. Overview of the proposed framework. The input to our framework is an image sequence. The pre-processing step is to remove the inhomogeneous background and noise. The three main modules in our framework are head detection, head registration, and flagellum tracing. These three modules perform sequentially to obtain the head trajectories and flagellar beat patterns for sperm motility analysis. Note that the output of the head registration module is image sequences for each individual sperms in which the heads are registered. Here, we show the minimum intensity projection (MinIP) of the image sequence.



Figure 4. Original confocal microscopy image of an axonal tree (left) and its tracing (right) (maximum intensity projections).

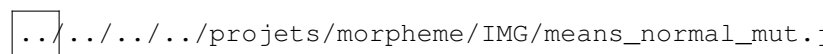


Figure 5. Mean normal (left) and mutant (right) axonal trees (2D projections).

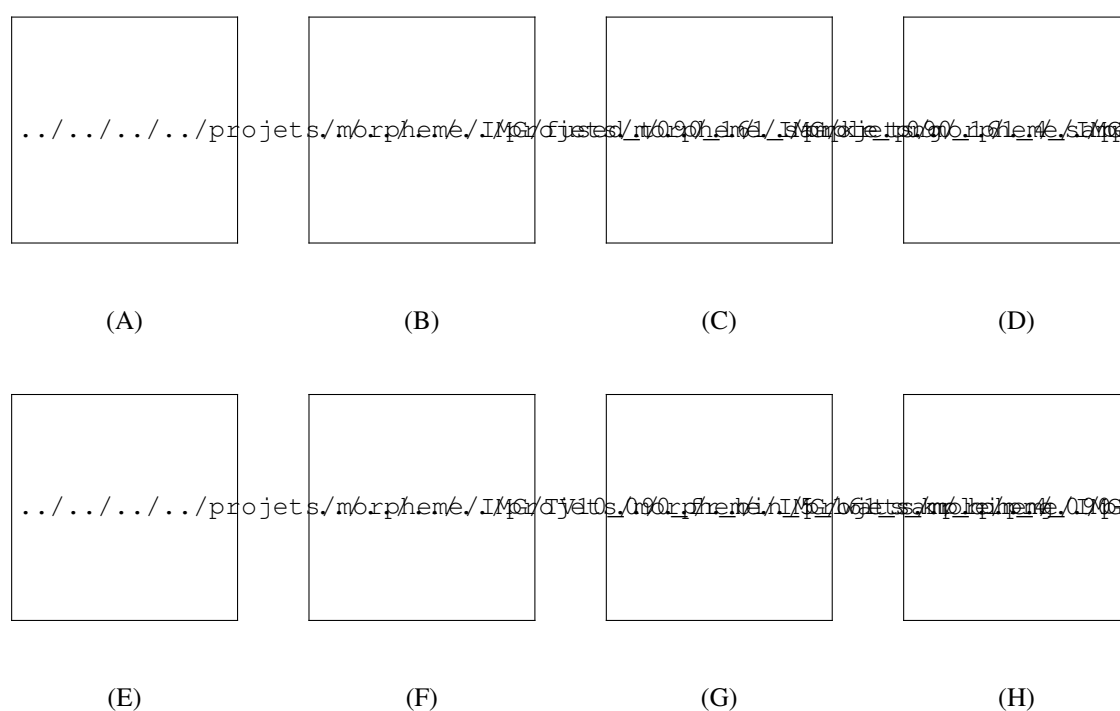


Figure 6. Illustrations of the different steps of the algorithm: (A) a 2D slice of original image, (B) the resulting surface detector response, (C) the directional extrema of the response image, (D) the deduced binarisation of the cell membranes, (E) the result of Tensor Voting applied to binarised image, (F) the cells segmentation computed from (E), (G) a 3D view of original image, (H) a 3D view of the cells segmentation.

4.6. Spatio-temporal registration of embryo images

Participants: Grégoire Malandain, Léo Guignard [Virtual Plants], Christophe Godin [Virtual Plants].

This work is made in collaboration with Patrick Lemaire (CRBM).

Current imaging techniques can capture temporal sequences of 3D images with very high time resolution over several hours. Comparing sequences covering the same time period opens the way to the study of developmental variability. Stitching together sequences captured from different embryos may help producing a sequence covering the whole development of the animal of interest. For this, it is necessary to align two sequences in both time and space.

We developed a method to align two 3D+t time series, based on the detection and pairing of 3D+t landmarks. These landmarks, which correspond to periods of fast morphogenetic change, are deduced from the analysis of the non-linear transformations that allow to co-register pairs of consecutive 3D images in each sequence (see figure 7). [12].

4.7. Characterizing cell membrane properties

Participants: Sylvain Prigent, Xavier Descombes, Grégoire Malandain, H el ene Barelli [IPMC].

Some mammalian cells show striking differences in the acyl chain composition of their membrane phospholipids. In most cases, the majority of phospholipids bear one saturated and one monounsaturated acyl chains at positions 1 and 2 or the glycerol, respectively. However, some cells and notably neurons contain large amounts of phospholipids with a polyunsaturated fatty acyl chain, generally at position 2. The aim of this work is to compare the impact of the phospholipid polyunsaturation vs monounsaturation on the mechanical and functional properties of the plasma membrane.

For this task, we currently investigate how phospholipid insaturation affects the ability of specialized protein machineries involved in transport vesicle formation, by first detecting vesicles in 2D+t sequences of microscopic images of individual cells, and then tracking detected vesicles through the temporal sequences (see figure 8) [23].

4.8. Tracking growing axons in 3D+t fluorescent two-photon microscopy images

Participants: Sylvain Prigent, Xavier Descombes [contact], Florence Besse, Caroline Medioni.

During the maturation of the nervous system, neuronal cells emit cellular extensions (dendrites, axons) allowing them to connect to other neurons, and thus, establish a network in which information is transmitted and/or stored. The formation of axonal extensions and directed migration of these extensions are two key processes controlling the morphology of neuronal cells, and then the number and nature of partners in a given network within a neuron. These two processes are controlled by both external factors to neuronal cell (guidance molecules, neurotrophic signals, ...) and internal factors (transcription factors, post-transcriptional regulators, regulators of the actin cytoskeleton or microtubules, ...). The goal of this work is to automatically extract axonal trajectories from images to then be able to model the processes controlling the morphology of neuronal cells.

The images we use are 3D+t images of growing drosophila brains obtained with a bi-photon confocal microscope. A single movie is about 200 3D frames that correspond to an acquisition every 5 minutes.

The developed method to extract axonal trajectories from 3D+t images is made of 3 main steps. The first step is to detect axonal tips on each 3D frame of the movie. This detection is performed using Marked Point Process. We designed a dedicated model based on an ellipse shape, a prior of no-overlapping between detected ellipses, and a data term calculated by:

$$d = \min(d_B(R_0, R_1), d_B(R_0, R_2), \max(d_B(R_0, R_3), d_B(R_0, R_4)))$$



Figure 7. Spatio-temporal registration of two time-series of embryo. Enlarged renderings indicate the registered timepoints. Notice that the temporal registration is not linear since the interval length between two registered time is different from one embryo to the next.



Figure 8. Left: detection of individual vesicles in one image of the sequence. Right: resulting paths of tracked vesicles through the $2D+t$ sequence.

where d_B denote the Bhattacharyya distance, R_0 the set of pixels inside the ellipse and R_1, R_2, R_3, R_4 four sets of pixels obtained by partitioning the ellipse contour into 4 regions around the ellipse vertex (see figure 9).

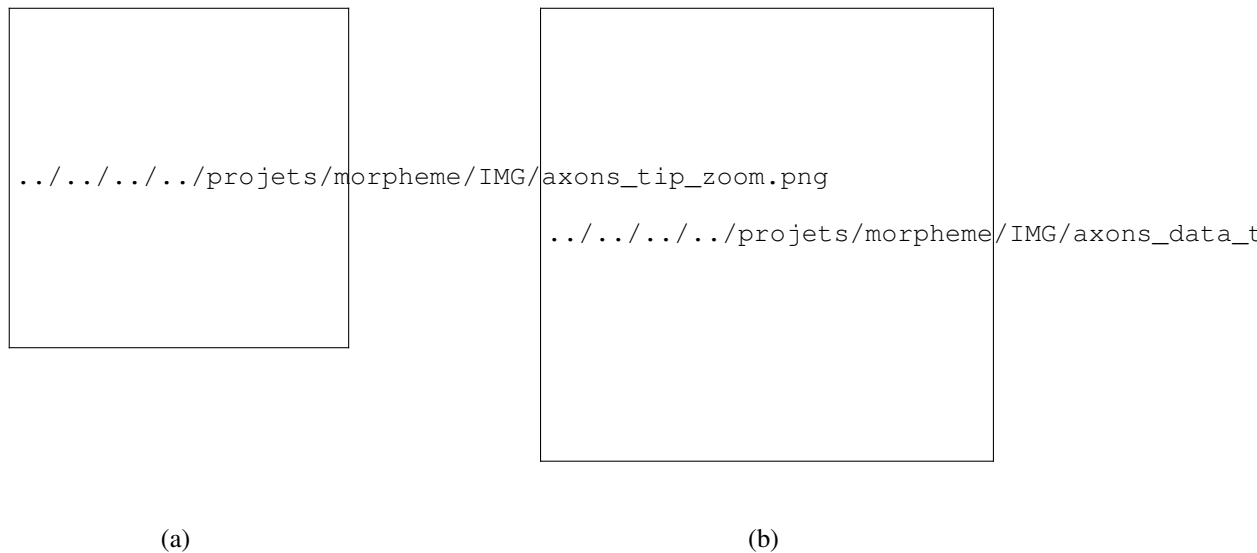


Figure 9. (a) Zoom on an axon tip. (b) Proposed ellipse model to detect an axon tip.

The second step consists to track the axons along the time frames by linking the tips detections. We designed an association tracking algorithm that builds a graph by connecting spatially close detections in neighboring frames. Negative costs have been introduced to favor long tracks. Then we ran sequentially the shortest path algorithm on this graph to obtain axons trajectories (see figure 10 (b)).

As the axonal tips size is close to the image resolution, the proposed method as the drawback to give false alarms trajectories. We then added a last processing step that aim to analyze the trajectories and remove those that do not correspond to axonal trajectories. This filtering removes three types of trajectories: 1) the trajectories that follow static regions of the image, 2) the short trajectories (less than 5 frames) and 3) random walk trajectories. An example of final automatic tracking is shown in figure 10 (c).



Figure 10. (a) 2D projection of the last frame. (b) Obtained tracks using the association tracking method. (c) Obtained tracks after false alarms removing.

4.9. A Hierarchical, Graph-cut-based Approach for Extending a Binary Classifier to Multiclass – Illustration with Support Vector Machines

Participants: Alexis Zubiolo, Eric Debreuve, Grégoire Malandain.

The problem of automatic data classification is to build a procedure that maps a datum to a class, or category, among a number of predefined classes. The building of such a procedure is the learning step. Using this procedure to map data to classes is referred to as classification or prediction. The procedure is therefore a classification, or prediction, rule. A datum (text document, sound, image, video, 3-dimensional mesh...) is usually converted to a vector of real values, possibly living in a high-dimensional space, also called signature. Offline, supervised learning relies on a learning set and a learning algorithm. A learning set is a set of signatures that have been tagged with their respective class by an expert. The learning algorithm input is formed by this set together with some parameters, its output being a prediction rule. Some learning algorithm, or method, apply only to the 2-class case. Yet, adapting such a binary classifier to a multiclass context might be preferred to using intrinsically multiclass algorithms, for example if it has strong theoretical grounds and/or nice properties; if free, fast and reliable implementations are available...The most common multiclass extensions of a binary classifier are the one-versus-all (OVA) (or one-versus-rest) and one-versus-one (OVO) approaches. In any extension, several binary classifiers are first learned between pairs of groups of classes. Then, all or some of these classifiers are called when predicting the classes of new samples. When the number of classes increases, the number of classifiers involved in the learning and the prediction steps becomes computationally prohibitive. Hierarchical combinations of classifiers can limit the prediction complexity to a logarithmic law in the number of classes (at best). Combinatorial approaches can be found in the literature. Because of their high learning complexity, these approaches are often disregarded in favor of an approximation trading optimality for computational feasibility. In our work, the high combinatorial complexity is overcome by formulating the hierarchical splitting problems as optimal graph partitionings solved with a minimal cut algorithm. In fact, as this algorithm performs only few additions and comparisons, its impact on the whole procedure is not significant. A modified minimal cut algorithm is also proposed in order to encourage balanced hierarchical

decompositions (see Fig. 11). The proposed method is illustrated with the Support Vector Machine (SVM) as the binary classifier. Experimentally, it is shown to perform similarly to well-known multiclass extensions while having a learning complexity only slightly higher than OVO and a prediction complexity ranging from logarithmic to linear. This work has been accepted to the International Conference on Computer Vision Theory and Application (VISAPP 2014) [20].



Figure 11. Type of tree that the proposed method builds during the learning stage (illustration with 5 classes). An example of classification of a new image signature is also illustrated by showing the visited nodes in boldface (read from root to leaf).

4.10. Classification of neurons to study Parkinson's disease

Participants: Alexis Zubiolo, Eric Debreuve, Xavier Descombes.

This work has been made in collaboration with Michèle Studer's team at iBV

In this project, the goal is to perform unsupervised classification of rat neurons in order to study the Parkinson's disease. The Institut de Biologie Valrose (iBV) provided us with 3-D images of rat cortices obtained by confocal microscopy. The discriminant features between normal and pathological neurons include the number of dendrites, the length and diameter of the apical dendrite, the shape and size of the soma. . . For each neuron, these features have to be computed automatically from the images. The specificity of this problem is that, for each rat cortex, we are given several images:

- one low resolution (LR) image which shows an overall view of the cortex and allows to compute the features related to the apical dendrite;
- some high resolution (HR) images (typically between 4 and 6) which provide close-ups of the somas of the neurons and allow to compute the other features.

This work consists in (1) extracting the neurons from the images (see Fig. 12), (2) matching the corresponding neurons in the HR and the LR images, (3) computing the features for each neuron, and (4) classifying the neurons, for example using a kernel Support Vector Machine (SVM).



Figure 12. Extraction of the neurons from the high-resolution image.

4.11. Curve and graph classification using a specific metric and kernel Support Vector Machines

Participants: Vladimir Gutov, Eric Debreuve, Xavier Descombes.

The analysis and comparison of trees are of great importance since many natural structures can be described using such models. In biology, lung airways, neurons, blood vessels... can be represented by trees (or, more generally, by graphs). Starting from a biological problem (automatically classifying neurons as wild or mutant), we studied the question of using Support Vector Machines (SVM) to classify continuous data such as curves, trees and graphs. Indeed, SVMs are designed for discrete data, looking for an optimal separation hyperplane or manifold in a discrete normed space. Manifolds are found when the original, linear SVM formulation is extended using the so-called kernel trick. The Gaussian kernel is the most popular one. By definition, the isotropic Gaussian kernel involves the two sample data to be compared through the distance between them. This opens the application of Gaussian-kernelized SVMs to any normed space. When dealing with (continuous) curves, the Fréchet distance can be used. We also tested a metric based on shape analysis [34]. Finally, a (meta-)distance between trees proved to be efficient in comparing axons [33] (see Fig. 13). The “meta” qualifier means that this distance builds upon a metric between curves and is valid for any such metric. It was tested using the shape-based metric [34]. We adapted an open-source SVM implementation to be able to use the three aforementioned metrics (two between curves, one between trees) and we validated the classification approach on synthetic data and on a small database of 20 wild-type neurons and 24 mutants provided by biologists.

4.12. Random forests for zooplankton classification

Participant: Eric Debreuve.

This work has been made in collaboration with Florent Baronian (Engineering student), Luc Deneire (I3S) and Marc Picheral (LOV)



Figure 13. Left: Axonal tree imaged with a confocal microscope (maximum intensity projection of the 3-D acquisition). Right: Manual extraction of the axon.

An UVP embedded system (Underwater Vision Profiler) is a device mainly composed of a digital camera with a fixed focal distance, and a flash system designed to illuminate only the focal plane. The device is attached to a boat by a cable and it is let going deep to take pictures at various depths. The purpose of such acquisition campaigns is to analyze the population of zooplankton organisms in different oceanic regions (see Fig. 14). The fifth version of the UVP developed at the Laboratoire d'Océanographie de Villefranche (LOV) only stores the pictures. All the processing is done offline: zooplankton organisms are segmented, features are extracted and a classification into types of organisms is performed. With the upcoming sixth version, the goal is to make the device smaller, lighter, and autonomous (for some time) in order to be placed in appliances designed to drift or navigate autonomously for weeks or months. This imposes to perform all the image processing tasks aboard, which limits the available processing power. Our work is to propose a classification method taking into account the constraints given by the teams in charge of the hardware design. We implemented a Random forest-based classifier which combines both good performances and low computational requirements. Since the images contain a lot of spurious objects called aggregates, we proposed a two-stage approach: the first stage is either a binary classifier or model checker tailored to eliminate the aggregates, while the second stage actually classifies the zooplankton organisms. We tested a combination of a one-class SVM (model checker) and a Random forest, and a combination of two Random forests, the first one being restricted to a binary classifier. Results were encouraging.



Figure 14. Left: Version 5 of the UVP embedded system (Underwater Vision Profiler) used to take pictures of the zooplankton at different depths. Right: Some organisms composing the zooplankton (Lars Stemann, LOV). Images acquired by the UVP have a much worse resolution.

4.13. Detection of Hedgehog protein using confocal imaging

Participants: Sylvain Prigent, Xavier Descombes.

This work was made in collaboration with P. Therond's group at iBV

P. Therond's lab is focusing on the understanding of how the secreted Hedgehog (Hh) morphogen, a dually lipidated highly hydrophobic molecule bound to membranes, is secreted, released and transported from the place of production in *Drosophila*. High resolution microscopy developed to identify and visualize such processes was successfully applied to address this question, but dynamics of membrane transport is still poorly understood mainly due to the lack of a reliable model or the need of fixation.

To statistically quantify the position of a population of Hedgehog proteins inside a cell, we need an automatic image processing method that detect each individual Hedgehog proteins in a 3D confocal image. The 3D images are obtained either by scanning Z slices (see figure 15), or by scanning XY slices (see figure 16). For both types of images, we used Marked Point Process (MPP) to detect 2D objects independently on each frame since proteins appear only in one slice. Using the Z slices, we observed that proteins appear as vertical rectangles whose size is close to the image resolution. We then design an MPP model to search for a configuration of vertically oriented rectangles that do not overlap one to each other. To define a data term for a given rectangle in the image, we calculate the Bhattacharyya distance between the population of pixels inside the rectangle and the population of pixels in the border of the rectangle. For the XY slices, we defined an MPP model to search for circles that do not overlap one to each other, and the data term is calculated with the Bhattacharyya distance as for the rectangle model. Examples of obtained results are shown in figures 15 and 16.

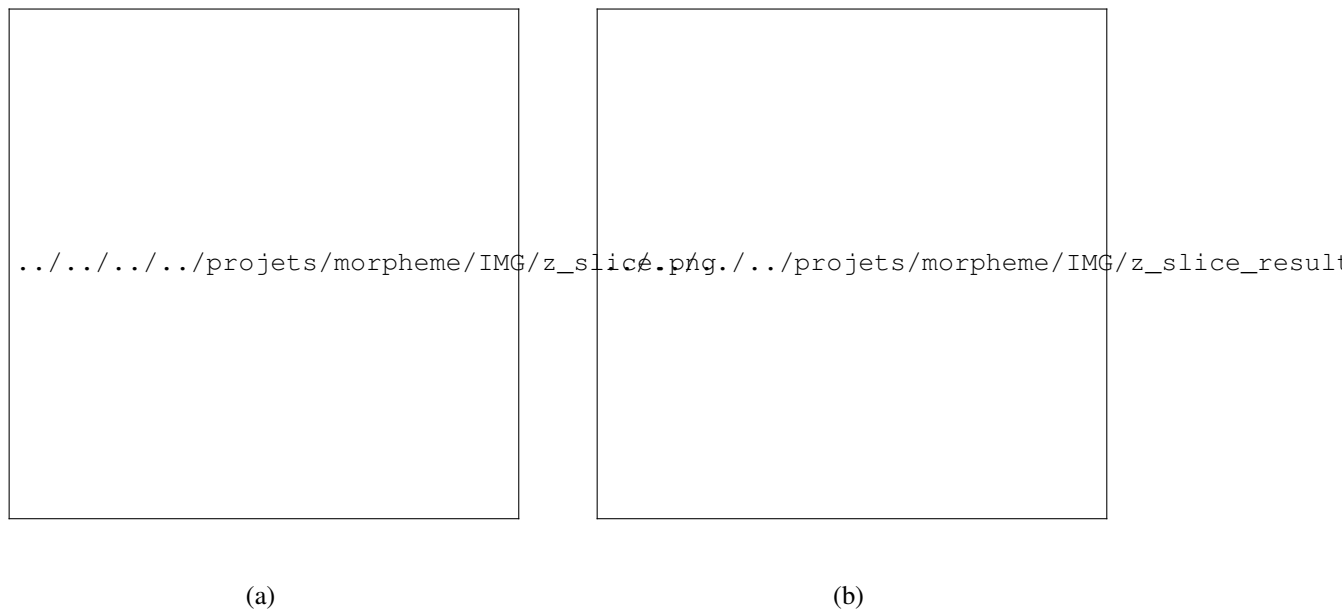


Figure 15. Example of proteins detection on a single z image slice (a) Original z slice. (b) Obtained proteins detection.

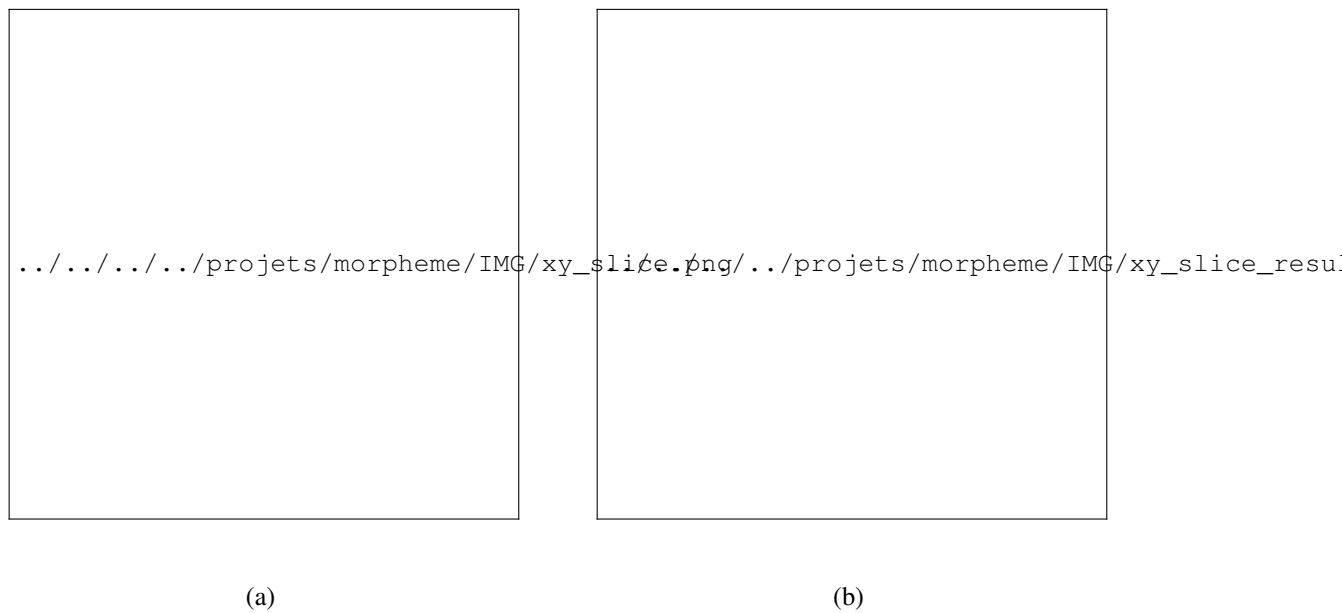


Figure 16. Example of proteins detection on a single xy image slice (a) Original xy slice. (b) Obtained proteins detection.

NEUROMATHCOMP Project-Team

5. New Results

5.1. Neural Networks as dynamical systems

5.1.1. Dynamics and spike trains statistics in conductance-based Integrate-and-Fire neural networks with chemical and electric synapses

Participants: Bruno Cessac, Rodrigo Cofré.

We investigate the effect of electric synapses (gap junctions) on collective neuronal dynamics and spike statistics in a conductance-based Integrate-and-Fire neural network, driven by a Brownian noise, where conductances depend upon spike history. We compute explicitly the time evolution operator and show that, given the spike-history of the network and the membrane potentials at a given time, the further dynamical evolution can be written in a closed form. We show that spike train statistics is described by a Gibbs distribution whose potential can be approximated with an explicit formula, when the noise is weak. This potential form encompasses existing models for spike trains statistics analysis such as maximum entropy models or Generalized Linear Models (GLM). We also discuss the different types of correlations: those induced by a shared stimulus and those induced by neurons interactions. This work has been presented in several conferences [40], [39], [39], [15] and published in Chaos, Solitons and Fractals [17].

5.2. Mean field approaches

5.2.1. Asymptotic description of neural networks with correlated synaptic weights

Participants: Olivier Faugeras, James Maclaurin.

We study the asymptotic law of a network of interacting neurons when the number of neurons becomes infinite. Given a completely connected network of neurons in which the synaptic weights are Gaussian correlated random variables, we describe the asymptotic law of the network when the number of neurons goes to infinity. We introduce the process-level empirical measure of the trajectories of the solutions to the equations of the finite network of neurons and the averaged law (with respect to the synaptic weights) of the trajectories of the solutions to the equations of the network of neurons. The main result of this work is that the image law through the empirical measure satisfies a large deviation principle with a good rate function which is shown to have a unique global minimum. Our analysis of the rate function allows us also to characterize the limit measure as the image of a stationary Gaussian measure defined on a transformed set of trajectories. This work is available on [ArXiv](#) and is under review for a Journal. A preliminary version has been presented at the CNS meeting [42].

5.2.2. Beyond dynamical mean-field theory of neural networks

Participants: Bruno Cessac, Massimiliano Muratori.

We consider a set of N firing rate neurons with discrete time dynamics and a leak term. The nonlinearity of the sigmoid is controlled by a parameter and each neuron has a firing threshold, Gaussian distributed (thresholds are uncorrelated). The network is fully connected with correlated Gaussian random synaptic weights, with mean zero and covariance matrix. When synaptic weights are uncorrelated the dynamic mean field theory allows us to draw the bifurcation diagram of the model in the thermodynamic limit (N tending to infinity): in particular there is sharp transition from fixed point to chaos characterized by the maximum Lyapunov exponent, which is known analytically in the thermodynamic limit. However, mean-field theory is exact only in the thermodynamic limit and when synaptic weights are uncorrelated. What are the deviations from mean-field theory observed when one departs from these hypotheses ? We have first studied the finite size dynamics.

For finite N the maximal Lyapunov exponent has a plateau at 0 corresponding to a transition to chaos by quasi-periodicity where dynamics is at the edge of chaos. This plateau disappears in the thermodynamic limit. Thus, mean-field theory neglects an important finite-sized effect since neuronal dynamics at the edge of chaos has strong implications on learning performances of the network. We also studied the effect of a weak correlation on dynamics. Even when correlation is small, one detects an important deviation on the maximal Lyapunov exponent. This work has been presented at the CNS conference in Paris, 2013 [43].

5.3. Neural fields theory

5.3.1. Existence of localized solutions

Participants: Pascal Chossat, Grégory Faye, James Rankin.

We have started to tackle the problem of rigorously proving the existence of localized solutions to the neural fields equations. Existence of such solutions had been assumed or guessed from numerical simulations by other researchers. In a series of articles starting with [55] we have used ideas from the theory of ordinary differential equations (existence of homoclinic orbits) [56], [19], and the theory of partial differential equations (Swift-Hohenberg equation) [16] to show the existence of localized solutions for an extended variety of neural fields equations. This is important both theoretically and for neuroscience since these solutions are considered to characterize working (short-term) memory.

5.3.2. A Center Manifold Result for Delayed Neural Fields Equations

Participants: Olivier Faugeras, Romain Veltz.

We have developed a framework for the study of delayed neural fields equations and proved a center manifold theorem for these equations. Specific properties of delayed neural fields equations make it difficult to apply existing methods from the literature concerning center manifold results for functional differential equations. Our approach for the proof of the center manifold theorem uses the original combination of results from Vanderbauwhede et al. [1992] together with a theory of linear functional differential equations in a history space larger than the commonly used set of time-continuous functions. This work has appeared in the SIAM Journal on Mathematical Analysis [24].

5.3.3. Interplay between synaptic delays and propagation delays in neural fields equations

Participant: Romain Veltz.

Neural field equations describe the activity of neural populations at a mesoscopic level. Although the early derivation of these equations introduced space dependent delays coming from the finite speed of signal propagation along axons, there has been few studies concerning their role in shaping the nonlinear dynamics of neural activity. This is mainly due to the lack of analytical tractable models. On the other hand, constant delays have been introduced to model the synaptic transmission and the spike initiation dynamics. By incorporating the two kind of delays in the neural fields equations, we are able to find the Hopf bifurcation curves analytically which produce many Hopf-Hopf interactions. We use normal theory to study two different types of connectivity that reveals a surprisingly rich dynamical portrait. In particular, the shape of the connectivity strongly influences the spatiotemporal dynamics. This work has appeared in SIAM Journal on Applied Dynamical Systems [25].

5.3.4. Stochastic neural field equations: A rigorous footing

Participants: James Inglis, Olivier Faugeras.

We extend the theory of neural fields which has been developed in a deterministic framework by considering the influence spatio-temporal noise. The outstanding problem that we address here is the development of a theory that gives rigorous meaning to stochastic neural field equations, and conditions ensuring that they are well-posed. Previous investigations in the field of computational and mathematical neuroscience have been numerical for the most part. Such questions have been considered for a long time in the theory of stochastic partial differential equations, where at least two different approaches have been developed, each having its advantages and disadvantages. It turns out that both approaches have also been used in computational and mathematical neuroscience, but with much less emphasis on the underlying theory. We present a review of two existing theories and show how they can be used to put the theory of stochastic neural fields on a rigorous footing. We also provide general conditions on the parameters of the stochastic neural field equations under which we guarantee that these equations are well-posed. In so doing, we relate each approach to previous work in computational and mathematical neuroscience. We hope this will provide a reference that will pave the way for future studies (both theoretical and applied) of these equations, where basic questions of existence and uniqueness will no longer be a cause for concern. This work is available on [ArXiv](#) and is under review for a Journal.

5.4. Spike trains statistics

5.4.1. Decoding the retina with the first wave of spikes

Participants: John Barrett [Institute of Neuroscience, Medical School, Newcastle University, Newcastle UK], Pierre Kornprobst, Geoffrey Portelli, Evelyne Sernagor [Institute of Neuroscience, Medical School, Newcastle University, Newcastle UK].

Understanding how the retina encodes visual information remains an open question. Using MEAs on salamander retinas [60] showed that the relative latencies between some neuron pairs carry sufficient information to identify the phase of square-wave gratings (Using gratings of varying phase, spatial frequency, and contrast on mouse retinas, we extended this idea by systematically considering the relative order of all spike latencies, i.e. the shape of the first wave of spikes after stimulus onset. The discrimination task was to identify the phase among gratings of identical spatial frequency. We compared the performance (fraction correct predictions) of our approach under classical Bayesian and LDA decoders to spike count and response latency of each recorded neuron. Best results were obtained for the lowest spatial frequency. There, results showed that the spike count discrimination performance was higher than for latency under both the Bayesian ($0,95\pm 0,02$ and $0,75\pm 0,11$ respectively) and LDA ($0,95\pm 0,01$ and $0,62\pm 0,03$ respectively) decoders. The first wave of spikes decoder is ($0,46\pm 0,06$) less efficient than the spike count. Nevertheless, it accounts for 50% of the overall performance. Interestingly, these results tend to confirm the rank order coding hypothesis [59] which we are currently investigating further.

This work has been presented in [45].

5.4.2. Spike train statistics from empirical facts to theory: the case of the retina

Participants: Bruno Cessac, Adrian Palacios [CINV-Centro Interdisciplinario de Neurociencia de Valparaiso, Universidad de Valparaiso].

This work focuses on methods from statistical physics and probability theory allowing the analysis of spike trains in neural networks. Taking as an example the retina we present recent works attempting to understand how retina ganglion cells encode the information transmitted to the visual cortex via the optical nerve, by analyzing their spike train statistics. We compare the maximal entropy models used in the literature of retina spike train analysis to rigorous results establishing the exact form of spike train statistics in conductance-based Integrate-and-Fire neural networks. This work has been published in *Mathematical Problems in Computational Biology and Biomedicine*, F. Cazals and P. Kornprobst, Springer [29].

5.4.3. Hearing the Maximum Entropy Potential of neuronal networks

Participants: Bruno Cessac, Rodrigo Cofré.

We consider a spike-generating stationary Markov process whose transition probabilities are known. We show that there is a canonical potential whose Gibbs distribution, obtained from the Maximum Entropy Principle (MaxEnt), is the equilibrium distribution of this process. We provide a method to compute explicitly and exactly this potential as a linear combination of spatio-temporal interactions. The method is based on the Hammersley Clifford decomposition and on periodic orbits sampling. As an application, we establish an explicit correspondence between the parameters of the Ising model and the parameters of Markovian models like the Generalized-Linear Model. This work has been presented in several conferences [39], [27], and submitted to Phys. Rev. Letters [41], see also the research report [31].

5.4.4. Spatio-temporal spike trains analysis for large scale networks using maximum entropy principle and Monte-Carlo method

Participants: Bruno Cessac, Olivier Marre [Institut de la Vision, Paris, France], Hassan Nasser.

Understanding the dynamics of neural networks is a major challenge in experimental neuroscience. For that purpose, a modelling of the recorded activity that reproduces the main statistics of the data is required. We present a review on recent results dealing with spike train statistics analysis using maximum entropy models (MaxEnt). Most of these studies have been focusing on modelling synchronous spike patterns, leaving aside the temporal dynamics of the neural activity. However, the maximum entropy principle can be generalized to the temporal case, leading to Markovian models where memory effects and time correlations in the dynamics are properly taken into account. We also present a new method based on Monte-Carlo sampling which is suited for the fitting of large-scale spatio-temporal MaxEnt models. The formalism and the tools presented will be essential to fit MaxEnt spatio-temporal models to large neural ensembles. This work has been presented in several conferences [39], [15], [44] and published in Journal of Statistical Mechanics [20].

5.4.5. Spike train statistics and Gibbs distributions

Participants: Bruno Cessac, Rodrigo Cofré.

We introduce Gibbs distribution in a general setting, including non stationary dynamics, and present then three examples of such Gibbs distributions, in the context of neural networks spike train statistics: (i) Maximum entropy model with spatio-temporal constraints; (ii) Generalized Linear Models; (iii) Conductance based Integrate and Fire model with chemical synapses and gap junctions. This leads us to argue that Gibbs distributions might be canonical models for spike train statistics analysis. This work has published in J. Physiol. Paris [15].

5.4.6. A maximum likelihood estimator of neural network synaptic weights

Participants: Bruno Cessac, Wahiba Taouali.

Given a conductance-based Integrate-and-Fire model where the spike statistics dependence on synaptic weights is known, can one reconstruct this network of synaptic weights from the observation of a raster plot generated by the network ? We have solved this inverse problem using an explicit expression of a maximum likelihood estimator based on the Newton-Raphson method. This estimator uses analytically computed gradients and Hessian of the likelihood function given by the product of conditional probabilities. The explicit form of these conditional probabilities can be found in [49]. Our results show that this method allows to estimate the set of connections weights knowing the input, the noise distribution and the leak function. This work has been presented in the CNS conference in Paris, 2013 [47].

5.5. Synaptic plasticity

5.5.1. Effects of Cellular Homeostatic Intrinsic Plasticity on Dynamical and Computational Properties of Biological Recurrent Neural Networks

Participants: Hugues Berry, Bruno Cessac, Bruno Delord, Jérémie Naudé.

Homeostatic intrinsic plasticity (HIP) is a ubiquitous cellular mechanism regulating neuronal activity, cardinal for the proper functioning of nervous systems. In invertebrates, HIP is critical for orchestrating stereotyped activity patterns. The functional impact of HIP remains more obscure in vertebrate networks, where higher-order cognitive processes rely on complex neural dynamics. The hypothesis has emerged that HIP might control the complexity of activity dynamics in recurrent networks, with important computational consequences. However, conflicting results about the causal relationships between cellular HIP, network dynamics and computational performance have arisen from machine learning studies. In this work, we assess how cellular HIP effects translate into collective dynamics and computational properties in biological recurrent networks. We develop a realistic multi scale model including a generic HIP rule regulating the neuronal threshold with actual molecular signaling pathways kinetics, Dale's principle, sparse connectivity, synaptic balance and Hebbian synaptic plasticity (SP). Dynamic mean-field analysis and simulations unravel that HIP sets a working point at which inputs are transduced by large derivative ranges of the transfer function. This cellular mechanism insures increased network dynamics complexity, robust balance with SP at the edge of chaos, and improved input separability. Although critically dependent upon balanced excitatory and inhibitory drives, these effects display striking robustness to changes in network architecture, learning rates and input features. Thus, the mechanism we unveil might represent a ubiquitous cellular basis for complex dynamics in neural networks. Understanding this robustness is an important challenge to unravel principles underlying self-organization around criticality in biological recurrent neural networks. This work has been published in the Journal of Neuroscience [21].

5.5.2. *Short-term synaptic plasticity in the deterministic Tsodyks-Markram model leads to unpredictable network dynamics*

Participants: Jesus Cortes, Mathieu Desroches, Serafim Rodrigues, Romain Veltz, Miguel Munoz, Terrence Sejnowski.

Short-term synaptic plasticity strongly affects the neural dynamics of cortical networks. The Tsodyks and Markram (TM) model for short-term synaptic plasticity accurately accounts for a wide range of physiological responses at different types of cortical synapses. We report a route to chaotic behavior via a Shilnikov homoclinic bifurcation that dynamically organizes some of the responses in the TM model. In particular, the presence of such a homoclinic bifurcation strongly affects the shape of the trajectories in the phase space and induces highly irregular transient dynamics; indeed, in the vicinity of the Shilnikov homoclinic bifurcation, the number of population spikes and their precise timing are unpredictable and highly sensitive to the initial conditions. Such an irregular deterministic dynamics has its counterpart in stochastic/network versions of the TM model: The existence of the Shilnikov homoclinic bifurcation generates complex and irregular spiking patterns and acting as a sort of springboard facilitates transitions between the down-state and unstable periodic orbits. The interplay between the (deterministic) homoclinic bifurcation and stochastic effects may give rise to some of the complex dynamics observed in neural systems.

This work has been published in the Proceedings of the National Academy of Sciences [52].

5.6. Visual Neuroscience

5.6.1. *Bifurcation Study of a Neural Fields Competition Model with an Application to Perceptual Switching in Motion Integration*

Participants: James Rankin, Andrew Meso [Institut de Neurosciences de la Timone, UMR 6193, CNRS, Marseille, France], Guillaume S. Masson [Institut de Neurosciences de la Timone, UMR 6193, CNRS, Marseille, France], Olivier Faugeras, Pierre Kornprobst.

In this work we have investigated the underlying mechanisms that gate multistable perception, by focusing on the presentation of 1:1 barber pole during long presentations, which is perceived to move in a direction that changes every few seconds. This phenomenon has been studied from the perspective of dynamical systems modeling and human psychophysics: From a modeling point of view, numerical tools from bifurcations analysis were applied to the study of a competition model posed as a feature-only neural field equation (with a continuous feature space) where adaptation and noise are implemented as mechanisms that can drive

activity switches. Human psychophysics experiments were jointly done by INT (Institut de Neurosciences de la Timone, Marseille): Human observers were presented a moving grating stimulus over 15s while eye movements and reports of perceptual switches were recorded. Investigating the stimulus contrast, we found that the peak in switching rate observed experimentally occurs close to a bifurcation in the model that separates two mechanistic regimes. By identifying signatures of the switching predicted by the model with the behavioural data at different parts of the transition-contrast curve, we found for the first time, evidence for a dominance of driving mechanisms which shifts from noise dominated at low contrasts to adaptation dominated at higher contrasts.

This work has been published in [22], [23].

5.6.2. A Retinotopic Neural Fields Model of Perceptual Switching in 2D Motion Integration

Participants: Pierre Kornprobst, Guillaume S. Masson [Institut de Neurosciences de la Timone, UMR 6193, CNRS, Marseille, France], Kartheek Medathati, James Rankin.

In perceptual multistability a fixed but ambiguous stimulus can invoke multiple interpretations although only one can be held at a time. Visual motion stimuli are inherently ambiguous, for instance due to the aperture problem, which makes motion perception a complex inference task. The underlying cortical dynamics that select one percept out of multiple competing possibilities are not fully understood. Recent studies by [22] and [68] have tried to address this problem using the neural fields formalism. In [22], a switching behaviour for a classical psychophysics stimulus, the multistable barberpole, was successfully captured in a feature-only, one-layer model of MT with adaptation and noise. However, without a representation of space, only some very specific stimulus could be considered. The work reported in [68] provides a much more general framework for motion integration in a two layer-model, however, it fails to capture the switching behaviour as the mechanisms of adaptation and noise were not considered. Building on the strengths of both studies, we propose a model that takes into account the spatial domain in a two-layer configuration whilst incorporating both adaptation and noise. Interactions between two layers processing local motion (V1 and MT) occurred through recurrent and lateral connections. The input stimuli are represented using direction of motion signals extracted using Reichardt detectors at corresponding 2D spatial locations. We use stimuli such as drifting bars and barberpoles to constrain the model to a suitable operating regime. In terms of computations, since the model is demanding, we implemented it using GPUs, extending the methods of [13]. Based on this implementation, we study dynamics of the model focusing on coherency in plaid motion (plaids and crossed barber pole).

This work has been presented in [28]

VIRTUAL PLANTS Project-Team

5. New Results

5.1. Analysis of structures resulting from meristem activity

5.1.1. Acquisition and design of plant geometry

Participants: Chakkrit Preuksakarn [Univ Kasertsart, Thailand], Mathilde Balduzzi, Frédéric Boudon, Christophe Pradal, Christophe Godin, Christian Fournier.

Virtual 3D model of plants are required in many areas of plant modeling. They can be used for instance to simulate physical interaction of real plant structures with their environment (light, rain, wind, pests, ...), to set up initial conditions of growth models or to assess their output against real data. In the past decade, methods have been developed to digitize plant architectures in 3D [59], [53]. These methods are based on direct measurements of position and shape of every plant organ in space. Although they provide accurate results, they are particularly time consuming. More rapid and automated methods are now required in order to collect plant architecture data of various types and sizes in a systematic way. In this aim, we explore the use of pictures, laser scanner, video and direct sketching.

- *Reconstruction of plant architecture from 3D laser scanner data.* (Chakkrit Preuksakarn, Mathilde Balduzzi, Frédéric Boudon, Christophe Godin, Pascal Ferraro [Labri, Bordeaux])

We investigate the possibility to use 3D laser scanners to automate plant digitizing. We are developing algorithms to reconstruct branching systems without leaves or foliage from scanner data or from scan simulated on plant mock-up obtained using different digitizing method.

For branching system, a number of automatic methods were proposed in the literature to reconstruct plausible branching structures from laser scanner data. The question of their assessment and accuracy is however critical for further exploitation in biological applications. For this, we developed an evaluation pipeline to assess reconstructions accuracy. A laser scan database on which experts built reference reconstructions is used as a basis of the evaluation. The pipeline is given two structures and compares both their elements and their organization. Similar elements are identified based on geometric criteria using an optimization algorithm. The organization of these elements is then compared and their similarity quantified. Two indices of geometrical and structural similarities are defined, and automatic reconstructions can thus be compared to reference structures to assess their accuracy. The method is successful at capturing the variation of similarities between two structures as different levels of noise are introduced. A first comparative evaluation of the different methods of the literature has been designed and conducted. This work has been presented at the FSPM conference and submitted at Annals of Botany for its special issue.

We also investigated the reconstruction of tree foliage from 3D scans. Such elements are crucial to study the interaction of the plant with its environment. However, laser scans contain outliers on the silhouette of the scans that make the meshing of the pointset difficult. New generation of laser scanners provide intensity of the laser reflected on the surface of scanned objects. This intensity depends of the distance to the object, its optical property and the incidence angle. A first work on this topic showed that after correcting the distance effect, the incidence angle can be deduced from the intensity. From this result, we developed a reconstruction pipeline using the scan intensities and based on Shape-From-Shading approaches. This work has also been presented at the FSPM conference.

- *Reconstruction from video.* (Frédéric Boudon, Jerome Guenard [IRIT, Toulouse], Geraldine Morin [IRIT, Toulouse], Pierre Gurdjos [IRIT, Toulouse], Vincent Charvillat [IRIT, Toulouse])



Figure 2. Reconstruction of a cherry tree. Left: photograph of the original tree. Right: 3D reconstruction from a laser scan rendered and integrated on the same background.

Even if mature computer vision techniques allow the reconstruction of challenging 3D objects from images, due to high complexity of plant topology, dedicated methods for generating 3D plant models must be devised. In collaboration with our colleagues from IRIT, Toulouse, we developed an analysis-by-synthesis method which generates 3D models of a plant from both images and a priori knowledge of the plant species.

Our method is based on a skeletonisation algorithm which allows to generate a possible skeleton from a foliage segmentation. Then, a 3D generative model, based on a parametric model of branching systems that takes into account botanical knowledge is built. This method extends previous works by constraining the resulting skeleton to follow hierarchical organization of natural branching structure. 3D models are then generated. A reprojection of the models can be compared with the original image to assess the visual accuracy of the reconstruction. We optimise the parameter values of the generative model based on the reprojection criterion. Realistic results are obtained on different species of plants, in particular vineyards. This work has been presented at the ISVC conference and published in LNCS [46].

- *Reconstruction of virtual fruits from pictures.* (Mik Cieslak, Nadia Bertin [Inra, Avignon], Frédéric Boudon, Christophe Godin, Michel Genard [Inra, Avignon], Christophe Goz-Bac [Université Montpellier 2])

This research theme is supported by the Agropolis project Fruit3D.

The aim of this work is to provide methods for generating fruit structure that can be integrated with models of fruit function and used to investigate such effects. To this end, we have developed a modeling pipeline in the OpenAlea platform that involves two steps: (1) generating a 3D volumetric mesh representation of the entire fruit, and (2) generating a complex network of vasculature that is embedded within this mesh. To create the 3D volumetric mesh, we use reconstruction algorithms

from the 3D mesh generation package of the Computational Geometry Algorithms Library (CGAL). To generate the pattern of vasculature within this volumetric mesh, we use a Space Colonisation Algorithm that populates the volume of the fruit by simulating competition for space of the vasculature. We have applied our modeling pipeline to generate the internal and external geometry of a cherry tomato fruit using Magnetic Resonance Imaging data as input. These studies demonstrate the possibility to create species-specific models of fruit structure with relatively low effort [31]. These volumetric meshes are then combined with models of function to form integrative computational fruit models, which will help to investigate the effects of fruit structure on quality (see section 5.3.2).

- *Reconstruction of root structures.* (Julien Diener, Frédéric Boudon, Christophe Pradal, Christophe Godin, Philippe Nacry [BPMP, INRA], Christophe Périn [AGAP, CIRAD], Anne Dievart [AGAP, CIRAD], Xavier Draye [UCL, Belgium])

Similarly to aerial part of plants, some needs for reconstruction procedure of root systems emerges. Most existing methods focus only on semi-automatic approaches. This does not support the high-throughput capabilities of acquisition systems. Within the Rhizopolis project (Agropolis foundation), we have designed an automatic analysis pipeline to extract root system architecture from images. This pipeline provides i) a model based segmentation method of the scanned image content (Petri plate, seeds, leaves and root pixels), ii) the extraction of a graph representation of the root system, and iii) a novel method to identifying the root axes organization.

5.1.2. Modeling the plant ontogenic programme

Participants: Christophe Godin, Yann Guédon, Evelyne Costes, Jean-Baptiste Durand, Anaëlle Ambreville, Pierre Fernique, Christophe Pradal, Jean Peyhardi, Catherine Trottier, Yassin Refahi, Etienne Farcot.

This research theme is supported by two PhD programmes.

The remarkable organization of plants at macroscopic scales may be used to infer particular aspects of meristem functioning. The fact that plants are made up of the repetition of many similar components at different scales, and the presence of morphological gradients, e.g. [48], [54], [55], [52], provides macroscopic evidence for the existence of regularities and identities in processes that drive meristem activity at microscopic scales. Different concepts have been proposed to explain these specific organizations such as "morphogenetic programme" [57], "age state" [51] or "physiological age" [50]. All these concepts state that meristem fate changes according to position within the plant structure and during its development. Even though these changes in meristem fate are specific to each species and lead to the differentiation of axes, general rules can be highlighted [51], [50]. Here we develop computational methods to decipher these rules.

- *Relating branching structure to the shoot properties* (Jean Peyhardi, Yann Guédon, Evelyne Coste, Catherine Trottier, Yves Caraglio [AMAP], Pierre-Eric Lauri [AGAP, AFEF team])

Shoot branching structures often take the form of a succession of homogeneous branching zones and have been analyzed using segmentation models such as hidden semi-Markov chains. Axillary meristem fates are influenced by local properties of the parent shoot such as for instance its growth rate or local curvature. The objective of this work, which is part of the PhD subject of Jean Peyhardi, is to develop statistical models that generalize hidden semi-Markov chains with the capability to incorporate explanatory variables that vary along the parent shoot (e.g. maximum growth rate of the leaf, surface of the leaf, length of the internode, local curvature of the parent shoot). More precisely, the simple multinomial distributions that represent the axillary productions observed in the different branching zones are replaced by multinomial generalized linear models (GLMs). Since the two classical categories of multinomial GLMs that correspond either to nominal or ordinal categorical response variables were not appropriate, we chose to develop a new family of multinomial GLMs called multi-step multinomial GLMs that enable to tackle partially ordered categorical response variables. Typically, we need to distinguish different timing of branching (e.g. immediate shoot, one-year-delayed shoot and latent bud), different categories of offspring shoots (e.g. among one-year-delayed shoots, vegetative short shoot, vegetative long shoot and flowering shoot) and to specialize

the explanatory variables for certain categories of offspring shoots (e.g. the growth of the parent shoot influence the immediate offspring shoots but not the one-year-delayed offspring shoots). The resulting integrative models are called semi-Markov switching multi-step multinomial GLMs and are applied to different data sets corresponding mainly to fruit tree branching structures.

- *Genetic determinisms of the alternation of flowering in apple tree progenies.* (Jean-Baptiste Durand, Jean Peyhardi, Baptiste Guitton [AGAP, AFEF team], Yan Holtz [AGAP, AFEF team] Catherine Trottier, Evelyne Costes, Yann Guédon)

A first study was performed to characterize genetic determinisms of the alternation of flowering in apple tree progenies [34], [17]. Data were collected at two scales: at whole tree scale (with annual time step) and a local scale (annual shoot or AS, which is the portions of stem that were grown during the same year). Two replications of each genotype were available.

Indices were proposed for early detection of alternation during the juvenile phase. They were based on a trend model and a quantification of the deviation amplitudes and dependency, with respect to the trend. This allows to quantify alternation from the yearly numbers of inflorescences at tree scale.

However, phenotyping subsamples of AS sequences is more realistic in the framework of genotype selection. To model alternation of flowering at AS scale, a second-order Markov tree model was built. Its transition probabilities were modeled as generalized linear mixed models, to incorporate the effects of genotypes, year and memory of flowering for the Markovian part, with interactions between these components. Asynchronism of flowering at AS scale was also assessed using an entropy-based criterion.

This work started during the PhD's work of Baptiste Guitton. It was then extended in 2012 by Yan Holtz during this Master 2 internship, supervised by Evelyne Costes and Jean-Baptiste Durand. New progenies were considered, as well as the performance of approximating the descriptors at whole tree scale with those at AS scale. These descriptors allowed the identification of QTL zones involved in the control of flowering in apple trees.

As a perspective of this work, patterns in the production of children ASs (numbers of flowering and vegetative children) depending on the type of the parent AS must be analyzed using branching processes and different types of Markov trees, in the context of Pierre Fernique's PhD Thesis (see next item in Section 5.1.2).

- *Modeling branching patterns in fruit tree shoots through the characterization of their demographic properties* (Pierre Fernique, Jean-Baptiste Durand, Yann Guédon).

To test the effect of some properties of a given parent shoot on the properties of its children shoots, statistical models based on multitype branching processes were developed. This kind of dependence between parent and children shoots is frequently at stake in fruit trees, for which the number of flowering or vegetative children of a parent shoot depends on its nature, with potential interactions with other factors. Thus, controlling demographic patterns of the shoots (through varietal selection or crop management strategies) is expected to bring substantial improvements in the quantity and quality of yields.

Formally, the shoot properties are summed up using the notion of shoot state. The number of children shoots in each state is modeled through discrete multivariate distributions. Model selection procedures are necessary to specify parsimonious distributions. We developed an approach based on probabilistic graphical models to identify and exploit properties of conditional independence between numbers of children in different states, so as to simplify the specification of their joint distribution. The graph building stage was based on exploring the space of possible chain graph models, which required defining a notion of neighbourhood of these graphs. A parametric distribution was associated with each graph. It was obtained by combining families of univariate and multivariate distributions or regression models, and their mixtures. These families were chosen by selection model procedures among different parametric families [45], [32].

This work was carried out in the context of Pierre Fernique's first year of PhD (Montpellier 2 University and CIRAD). It was applied to model dependencies between short or long, vegetative or flowering shoots in apple trees. The results highlighted contrasted patterns related to the parent shoot state, with interpretation in terms of alternation of flowering (see previous item in Section 5.1.2). It was also applied to the analysis of the connections between cyclic growth and flowering of mango trees (see next item in Section 5.1.2). This work will be continued during Pierre Fernique's PhD thesis, with extensions to other fruit tree species and other parametric discrete multivariate families of distributions, including covariates and mixed effects.

- *Analyzing fruit tree phenology* (Anaëlle Dambreville, Jean-Baptiste Durand, Pierre Fernique, Yann Guédon, Christophe Pradal, Pierre-Eric Lauri [AFEF team, AGAP], Frédéric Normand, Catherine Trottier)

Mango is a tropical tree characterized by strong asynchronisms within and between trees. Causation networks explaining the vegetative and reproductive growths within and between growing cycles were studied on the basis of generalized linear models [16]. We highlighted in this way marked interplays between structural and temporal components of tree structure development at three scales. At growth unit scale, a growth unit which appeared early in the growing cycle had higher rate of burst compared to late appeared growth units. At growing cycle scale, a flowering growth unit delayed its future vegetative growth compared to a vegetative growth unit. At tree scale, a fruiting tree delayed further vegetative growth and flowering compared to a non-fruiting tree. These results evidenced that tree phenology is strongly affected by structural components and not only by the environment.

To study more precisely the interplays between all these structural components, we started during the internship of A. Jestin to build an integrative model to simulate the development of mango tree based on the L-system formalism and GLM to model the dependencies between events.

We are also investigating jointly structure development and phenology of mango, and characterizing the specific spatio-temporal patterns leading to patches of vegetative or flowering growth units. Our approach is based on statistical models for trees; particularly hidden Markov tree models and multitype branching processes [32].

- *Integrative developmental growth stages of shoots* (Anaëlle Dambreville, Yann Guédon, Pierre-Eric Lauri [AFEF team, AGAP], Frédéric Normand)

Growth and development are often studied as two separated processes. Our aim is to investigate the coordination between growth and development in mango shoots. We considered three types of organ, namely the shoot axis, its attached leaves and the inflorescence. Two types of data were collected during the shoot and inflorescence follow-up: developmental stages determined in an expert way and organs sizes determined from measurements. To give an integrative view of the shoot and inflorescence growth and development, we adopted the following strategy. For a given cultivar, we first built a multi-state model on the basis of absolute growth rate sequences deduced from the measurements. Using these models, we computed growth stages. These growth stages highlighted growth asynchronisms between two topologically-connected organs: the axis and its leaves. Then, we compared these growth stages with the developmental ones and we obtained strong matches between them. The integrated developmental growth stages emphasized that the developmental stages are markedly related to growth rates and can be interpreted in terms of physiological (hydraulics, carbohydrates partitioning) and developmental (organs preformation versus neoformation) processes.

- *Self-nested structure of plants*. (Christophe Godin, Romain Azais, Farah Ben Naoum, Jean-Baptiste Durand, Alain Jean-Marie)

In a previous work [5], we designed a method to compress tree structures and to quantify their degree of self-nestedness. This method is based on the detection of isomorphic subtrees in a given tree and on the construction of a DAG, equivalent to the original tree, where a given subtree class is represented only once (compression is based on the suppression of structural redundancies in the original tree). In the compressed graph, every node representing a particular subtree in the original

tree has exactly the same height as its corresponding node in the original tree. This method thus compresses a tree in width, but not in height. In this new work, we designed an extension of this compression method in which a tree is compressed in both width and height. The method is based on the detection of so-called *quasi-isomorphic paths* in a tree and on the compression of these paths in height. A paper describing the corresponding algorithms is being written.

We are currently studying how to generalize the previous approach using stochastic trees. The idea is to generalize the previously defined equivalence relation so that equivalent trees are identical in distribution now and are no longer strictly isomorphic. Algorithms to estimate the different distributions from tree samples rely on combinatorics arguments that are used to estimate the probability that an observed tree is produced by a particular stochastic tree model for which a conjecture has been proposed (still to be demonstrated). The asymptotic analysis of similar compression rates on ordered tree-graphs has been carried out by Flajolet et al. (1990) for different types of distributions (uniform, multi-type branching processes). The work is developed in the context of the Post-doc of Romain Azais.

5.1.3. Analyzing the influence of the environment on the plant ontogenic programme

Participants: Frédéric Boudon, Jean-Baptiste Durand, Christophe Godin, Yann Guédon, Jean Peyhardi, Pierre Fernique, Maryline Lièvre, Christine Granier, Evelyne Costes, Pascal Ferraro, Catherine Trottier.

This research theme is supported by three PhD programs.

The ontogenetic programme of a plant is actually sensitive to environmental changes. If, in particular cases, we can make the assumption that the environment is a fixed control variable (see section 5.1.2), in general the structure produced by meristem results from a tight interaction between the plant and its environment, throughout its lifetime. Based on observations, we thus aim to trace back to the different components of the growth (ontogenetic development and its modulation by the environment). This is made using two types of approaches. On the one hand, we develop a statistical approach in which stochastic models are augmented with additional time-varying explanatory variables that represent the environment variations. The design of estimation procedures for these models make it possible to separate the plant ontogenetic programme from its modulation by the environment. On the other hand, we build reactive models that make it possible to simulate in a mechanistic way the interaction between the plant development and its environment.

- *Influence of environment conditions and horticultural practices on the branching and axillary flowering structures of fruit tree shoots.* (Yann Guédon, Evelyne Costes [AFEF Team, AGAP], Ted DeJong [UC Davis], Claudia Negron [UC Davis]).

In the context of a collaboration with Claudia Negron and Ted DeJong, we studied the influence of water availability and pruning practices on the branching and axillary flowering structures of different categories of almond shoots. Stochastic models (hidden semi-Markov chains) were built for the branching and axillary flowering structures of different categories of almond shoots corresponding to different genetic backgrounds, levels of irrigation and pruning practices.

- *Analyzing growth components in trees.* (Yann Guédon, Yves Caraglio [AMAP], Olivier Taugourdeau [AMAP])

In a forest ecology context, we identified robust indicators that summarize the balance between tree ontogeny and environmental constraints (mainly related to light environment). In this context, tree growth data typically correspond to the retrospective measurement of annual shoot characteristics (e.g. length, number of branches) along the main stem. We applied segmentation models (hidden Markov and semi-Markov chains) that enable to identify tree growth phases. This statistical modeling approach was applied to both deciduous (sessile oak and Persian walnut) and evergreen (Corsican pine and silver fir) tree species growing in contrasted conditions ranging from managed forest stands to unmanaged understoreys. The growth phase duration distributions estimated within these segmentation models characterize the balance between tree ontogeny and the environmental constraints in tree development at the population scale. These distributions had very contrasted characteristics in terms of shape and relative dispersion between ontogeny-driven and environment-driven tree

development. The characteristics of growth phase duration distributions may change over tree life reflecting changes in tree competition.

- *Investigating how architectural development interfer with epidemics and epidemic control* (Christian Fournier, Corinne Robert [EGC], Guillaume Garin [ITK], Bruno Andrieu [EGC], Christophe Pradal)

Recent considerations towards sustainable agriculture require identifying new natural strategies of crop protection. In this perspective, a better identification of major interactions inside pathosystems between the plants, the pathogens and their environment is crucial. These multiscale biological systems are complex: multiple relationships stand out with various dynamics and at various locations in the canopy, related to its architectural development. The purpose of this research is to provide a framework to study the influence of architectural development on pathosystems with modeling. A first generic framework was designed and implemented in the platform OpenAlea [36]. It allows implementing pathogens of different kind using the same concepts, and a re-use of plant models available in Openalea, thus simplifying the development of pathosystem models based on 3D plants models. A second action was to develop a modular integrated model coupling architectural canopy development, disease dynamics, pesticide application, pesticide decay and effect of pesticide on disease dynamics [35]. This model is currently being assessed against data for validation, and aim at designing new strategies that reduce pesticide applications by increasing natural resistance linked to canopy architecture.

5.2. Meristem functioning and development

In axis 2 work focuses on the creation of a *virtual meristem*, at cell resolution, able to integrate the recent results in developmental biology and to simulate the feedback loops between physiology and growth. The approach is subdivided into several sub-areas of research.

5.2.1. Data acquisition and design of meristem models

Participants: Frédéric Boudon, Christophe Godin, Christophe Pradal, Léo Guignard, Vincent Mirabet [RDP, ENS], Jan Traas, Grégoire Malandain, Jean-Luc Verdeil [PHIV, AGAP].

This research theme is supported by the iSam and Morphogenetics projects.

- *Improvement of the MARS-ALT pipeline robustness* Meristem, laser microscopy, image reconstruction, cell segmentation, automatic lineaging

Participants: Léo Guignard, Christophe Godin, Christophe Pradal, Grégoire Malandain, Guillaume Baty, Jan Traas, Patrick Lemaire, Pradeep Das [RDP, ENS], Yassin Refahi [RDP, ENS].

The MARS-ALT (Multi-Angles Registration and Segmentation - Automatic Lineage Tracking) software pipeline automatically performs a segmentation at cell resolution from 3D or 2D voxel images where the membranes/walls are marked (by a dye for example) and makes it possible to follow the lineage of these cells through time [4]. A new version of this pipeline is currently being developed. MARS-ALT Version 2 is based on the same algorithms and methods and is intended to improve the overall robustness of the pipeline (protocol, noise in the input image) and automate completely the process. To test the new pipeline, we use different acquisition protocols and different organisms (floral and apical meristems and the early stages of development of a marine animal *Phallusia mammillata*). The segmentation is corrected a posteriori to deal with imaging artifacts due to uncertainties of acquisition. The image data set on which we develop the methods consists of :

- *Arabidopsis thaliana* shoot apical meristem and primordia with around 6000 cells. The organ is captured from three different angles every 4 hours during 2 or 3 days with a confocal microscope (Collaboration Sainsbury lab, Cambridge)
- *Arabidopsis thaliana* flower meristems with around 2000 cells. The organ is also captured from three different angles with a confocal microscope (Collaboration RDP Lyon and Sainsbury lab)

- *Phallusia mammillata* and *Ciona intestinalis* embryos with from 32 cells to around 1000 cells. The organism is captured from four different angles every minute during 2 to 3 hours with a SPIM (Single Plane Illumination Microscope) (Collaboration CRBM Montpellier / EMBL Heidelberg). This work is developed in the context of the PhD work of Léo Guignard.

The pipeline provides as an output segmented images on which metrics for each cells can be extracted such as volume, principal components, convex hull and more. A new non-linear registration algorithm developed by G. Malandain (MORPHEME team, Inria Sophia-Antipolis) is now available and will lead to an improvement of ALT algorithm. Redesign and improvement of the lineage tracking pipeline will be the next step.



Figure 3. Superimposition of an automatic cell segmentation of an arabidopsis flower meristem using the new MARS pipeline with the original confocal image stack where the membranes are marked.

- Design of 3D virtual atlases for specifying gene expression patterns (Yassin Refahi, Christophe Godin, Jan Traas, Patrick Lemaire, Grégoire Malandain, Françoise Monéger [RDP, ENS])

This research theme is supported the ANR GeneShape and iSam projects.

To organize the various genetic, physiological, physical, temporal and positional informations, we build a spatialized and dynamic database. This database makes it possible to store all the collected information on a virtual 3D structure representing a typical organ. Each piece of information has

to be located spatially and temporally in the database. Tools to visually retrieve and manipulate the information, quantitatively through space and time are being developed. For this, the 3D structure of a typical organ has been created at the different stages of development of the flower bud. This virtual structure contains spatial and temporal information on mean cell numbers, cell size, cell lineages, possible cell polarization (transporters, microtubules), and gene expression patterns. Such 3D virtual atlas is mainly descriptive. However, like for classical databases, specific tools make it possible to explore the virtual atlas according to main index keys, in particular spatial and temporal keys. Both a dedicated language and a 3D user interface are being designed to investigate and query the 3D virtual atlas.

A prototype version of the 3D virtual atlas was built 2 years ago [6]. Further developments of this tool will rely on the segmented images produced from microscopy, as presented in the previous section. In particular, a common underlying data structure has to be developed transversally to these two scientific developments. The definition of this data structure has been initiated last year through several team meetings, and should lead to a revised implementation next year.

5.2.2. *Shape analysis of meristems*

(Jonathan Legrand, Frédéric Boudon, Christophe Godin, Yann Guedon, Pradeep Das [ENS Lyon])

At cellular resolution, we studied the organization of cells in the meristems. The MARS-ALT pipeline provides rich spatio-temporal data sets for analyzing the development of meristems. A first step consisted of designing a dedicated graph for efficiently representing the spatial (adjacency between cells) and temporal (cell division) relationships between cells. Various variables can be attached either to the vertices (e.g. cell volume, inertia axes) or the edges (e.g. wall surface, distance between cell centroids). This graph may be augmented by new variables resulting from various spatial or temporal filtering (e.g. cell volumetric growth). We are now designing models and algorithms for finding patterns in time courses of meristems. In particular, we are investigating spectral clustering methods in order to define homogeneous regions in terms of cell identities in the context of the PhD Work of Jonathan Legrand.

5.2.3. *Transport models*

Participants: Michael Walker, Christophe Godin, Etienne Farcot, Jan Traas, Yuan Yuan [University of Newfoundland, Canada].

This research theme is supported by the ANR GeneShape and ERASysBio+ iSAM projects and Morphogenetics.

Active transport of the plant hormone auxin has been shown to play a key role in the initiation of organs at the shoot apex, and vein formation in both leaves and the shoot apical meristem. Polar localized membrane proteins of the PIN1 and AUX/LAX family facilitate this transport and observations and models suggest that the coherent organization of these proteins in the L1 layer is responsible for the creation of auxin maxima (surrounded by a depletion zone), which in turn triggers organ initiation close to the meristem center [58] [1]. Furthermore, canalized PIN allocations are thought to play a crucial role in vein formation in the leaf and in the L2. Previous studies have typically modeled the L1 and L2 with different models to explain different patterns of PIN allocations. In the last two years, we developed a unifying model showing that a unique flux-based model could be sufficient to explain PIN patterns in both L1 and L2 [27]. Contrary to our previous study [9], here no change in the model parameters is needed for this. Our approach is based on inherent topological and geometrical differences between the L1 and L2, specifically their dimensionality and the distribution of sources and sinks.

In a different perspective, another study on auxin transport models have been submitted this year. In this work, a generic, adimensional flux-based model of auxin transport was studied using a combination of analytic and numeric approach. The steady-states with uniform auxin distribution were characterised for arbitrary tissues, and some of their bifurcations (loss of stability and Hopf) were described [18]. This work, initiated during an "Explorateur" project funded by Inria during the period October 2012-January 2013, results from the collaboration between E. Farcot and Y. Yuan (Memorial University of Newfoundland, Canada).

5.2.4. Mechanical model

Participants: Olivier Ali, Christophe Godin, Benjamin Gilles, Frédéric Boudon, Jan Traas, Olivier Hamant [ENS-Lyon], Arezki Boudaoud [ENS-Lyon], Jérôme Chopard [University of Western Australia, Perth].

This research theme is supported by the ANR VirtualFlower and Geneshape projects together with the Inria project Morphogenetics and the ERC from Jan Traas.

The rigid cell walls that surround plant cells are responsible for their shape. These structures are under constraint due to turgor pressure inside the cell. To study the changes of shape in plant tissues during organogenesis, we need a mechanical model of tissue development at cellular resolution. We developed such a model, in which walls are characterized by their mechanical properties like the Young modulus which describes the elasticity of the material. Wall deformation results from forces due to turgor pressure. Growth results from cell wall synthesis that is triggered when wall deformation exceeds a particular threshold. The final shape of the tissue integrates mechanically all the local deformations of each cell.

To model this process, we used a tensorial approach to describe both tissue deformation and stresses. Deformations were decomposed into elementary transformations that can be related to underlying biological processes. However, we showed that the observed deformations does not map directly local growth instructions given by genes and physiology in each cell. Instead, the growth is a two-stage process where genes are specifying how cell walls should yield to mechanical stresses. In this way, different regions in the tissue with different cell identities can have different growth properties. The final shape of the tissue results from the integration of all these mechanical properties and stresses at organ level under the growth force due to turgor pressure at tissue scale.

A paper describing the mechanical model and its application to model primorium formation in the shoot apical meristem has been submitted to PNAS in December. Additionally, a redesign of our mechanical model using the SOFA framework is being finalized.

5.2.5. Gene regulatory networks

Modeling gene activities within cells is of primary importance since cell identities correspond to stable combination of gene expression [25].

- *Complex dynamics and spatial interactions in gene networks* (Yassin Refahi, Etienne Farcot, Christophe Godin)

Complex computational and mathematical questions arise in the study of gene networks at two levels: (i) the single cell level, due to complex, nonlinear interactions, (ii) the tissue level, where multiple cells interact through molecular signals and growth, so that even simple local rules can challenge our intuition at higher scales.

At the single cell level, new results were obtained in the framework of piecewise-linear models, it is in general very difficult to entirely characterize the attractors of a given system. In an attempt to improve our ability on this question, a probabilistic approach has been proposed in [14], in which it is shown that a Markov chain can be built as an approximation of a given piecewise-linear system, and actually used to make predictions about its periodic attractors.

At a higher scale, we have also continued the study of gene regulation in meristematic tissues. In the context of Y. Refahi's post-doc between Virtual Plants and the group of Henrik Jönsson in Cambridge (Sainsbury Laboratory), we have continued a work that was initiated in Y. Refahi's thesis. This work is motivated by recent biological results, indicating that gradient-like patterns originating from the external layers of meristems may play a decisive role in the specification of the pool of stem cells in a central position. Using the methods in [4], and their on-going improvements, we have acquired new 3D and 4D images that were then segmented. These structures will be used in the next few months to investigate generic patterning properties of gradient like morphogen patterns. This will require a thorough analysis of free diffusion in realistic geometries, as made possible by the newly acquired images. As a preliminary work, we are also currently investigating the formation of gradient patterns

in idealised tissues, allowing for deeper analytic treatment than the complex structures obtained by microscopy.

5.2.6. Model integration

Participants: Frédéric Boudon, Christophe Godin, Eugenio Azpeitia, Laurent Laplaze, Jan Traas, François Parcy.

This research theme is supported by the ANR/BBSRC project iSam.

Our approach consists of building a programmable tissue which is able to accept different modeling components. This includes a central data structure representing the tissue in either 2-D or 3-D, which is able to grow in time, models of gene activity and regulation, models of signal exchange (physical and chemical) between cells and models of cell cycle (which includes cell division). For each modeling component, one or several approaches are investigated in depth, possibly at different temporal and spatial scales, using the data available from the partners (imaging, gene networks, and expression patterns). Approaches are compared and assessed on the same data. The objective of each submodel component will be to provide plugin components, corresponding to simplified versions of their models if necessary, that can be injected in the programmable tissue platform. This work is developed in collaboration with the RDP group at ENS-Lyon [56] and the CPIB group in Nottingham, UK [49].

- *Development of a computer platform for the 'programmable tissue'.* (Frédéric Boudon, Christophe Godin)

One key aspect of our approach is the development of a computer platform dedicated to programming virtual tissue development. This platform will be used to carry out integration of the different models developed in this research axis. The platform is based on *OpenAlea*. Partner models can be integrated in the platform in a non-intrusive way (the code of their model need not be rewritten). In this context, model integration will i) consist of designing adequate data-structures at different levels that will be exchanged and reused among the different plug-in models and ii) defining control flows at adequate levels to avoid the burden of excessive interaction between components. In the past year, progress has been made in defining a generic tissue data structure that could be used in this platform, through several group meetings along the year. A redesign of the structure is in progress.

- *Design of a genetic model of inflorescence development.* (Etienne Farcot, Eugenio Azpeitia, Christophe Godin, François Parcy)

We studied the regulatory network that control flower development during morphogenesis. To overcome the network complexity and integrate this regulation during ontogenesis, we have developed a first model of the control of floral initiation by genes, and in particular the situation of cauliflower mutants, in which the repeatedly meristem fails in making a complete transition to the flower. This work couples models at different scales, since gene regulation is described by a minimal gene network, which is used as a decision module in an L-system model of the inflorescence architecture. This mixed model has led us to make different hypotheses about gene interactions and hormonal regulation. First predictions about gene actors controlling the passage to flower could be verified. A first integrated picture of flower development could be reached in the context of the internship of Eugenio Azpeitia (PhD Student).

5.3. Multi-scale models and analysis: from cells to plant architecture (and back)

5.3.1. Transport model in roots

Participants: Mikaël Lucas [IRD], Christophe Pradal, Christophe Godin, Christophe Maurel [BPMP].

This research theme is supported by the ANR project HydroRoot.

A model of *Arabidopsis thaliana* root hydraulics at the cellular level was developed in the OpenAlea modeling platform. The model relies on the integration throughout root architecture of elementary hydraulic components. Each component integrates local radial and axial water flows. Axial hydraulic conductivity is calculated according to Poiseuille's law, based on local size of xylem vessels. Radial hydraulic conductivity is determined in part by aquaporin activity and was set constant throughout root architecture in the first model versions. In its current state, the model is parameterized using architectural, tissular and physiological data that were experimentally determined in the Aquaporin group at BPMP. The architectural reconstruction of the root system is based on a tridimensional multi-scale tree graph (MTG). The current model is capable of predicting the water flow that is transported by a root system in the standard experimental conditions used in the Aquaporin group. This model was used to perform sensitivity analyses and determine the respective contributions to root hydraulic dynamics of various biological parameters (axial and radial hydraulic conductivities, root architecture). One major finding is that the root hydraulic conductivity (L_{pr}) computed from the model is highly dependent on root architecture. This is due to the limiting role of axial (xylem) conductance, one feature that had been neglected in previous representations of root water transport. The radial hydraulic conductivity may primarily be limiting in conditions of L_{pr} inhibition, since its increase from values in control roots has marginal effects on L_{pr} . A new set of experimental data including root diameter repartitions in wild-type plants, and xylem vessel diameters in mutants with altered xylem morphology (*irx3*, *esk1*) will be used to implement the model. Root cell hydraulic conductivities will also be measured in these and aquaporin mutant phenotypes. Our aim is to check whether, based on anatomical and morphological data, the model can properly predict the radial hydraulic conductivity of these genotypes.

5.3.2. Transport in fruits

Participants: Mik Cieslak, Nadia Bertin [Inra, Avignon], Frédéric Boudon, Christophe Godin, Michel Genard [Inra, Avignon], Christophe Goz-Bac [Université Montpellier 2].

This research theme is supported by the Agropolis project Fruit3D.

Understanding the controlling factors of fruit quality development is challenging, because fruit quality results from the interplay between physical and physiological processes that are under the control of genes and the environment. Although process-based models have been used to make significant progress in understanding these factors, they ignored to a large extent the shape and internal structure of the fruit.

To help characterizing effects of fruit shape and internal structure on quality, the creation of a 3D virtual fruit model that integrates fruit structure and function with growth governed by environmental inputs has been investigated. For this, a modeling pipeline has been developed that includes the following steps: creation of a 3D volumetric mesh of the internal fruit structure, including vasculature (see section 3). Based on previous compartment models of fruit physiology developed at Avignon, we have then developed models of water and carbon transport that have been coupled with the 3D model of fruit. In the 3D model, different equations are describing the transport between adjacent regions of the fruit represented as a 3D mesh. The integration through space and time is carried out using a standard integration scheme (Runge-Kutta of order 4).

This approach has been applied to study tomato fruit (*Solanum lycopersicum*) by constructing 3D volumetric meshes from different sources (images of perpendicular fruit slices and MRI data), and integrating water and carbon transport processes into these meshes. To illustrate the tomato model, a simulation of one season of the fruit's growth has been performed and its results compared with an already published process-based tomato fruit model. We first showed that our spatialized model is compliant with classical results of the abstract process-based models but also provides additional information on the internal heterogeneity of the fruit, such as a gradient in sugar concentration. Once the model is calibrated and evaluated, our approach will be suitable for studying the effects of internal fruit heterogeneity and overall shape on fruit quality development.

5.3.3. Analyzing root growth and branching

Participants: Beatriz Moreno Ortega, Sixtine Passot, Yann Guédon, Laurent Laplaze [IRD, DIADE], Mikaël Lucas [IRD, DIADE], Bertrand Muller [INRA, LEPSE].

This research theme is supported by two PhD programmes.

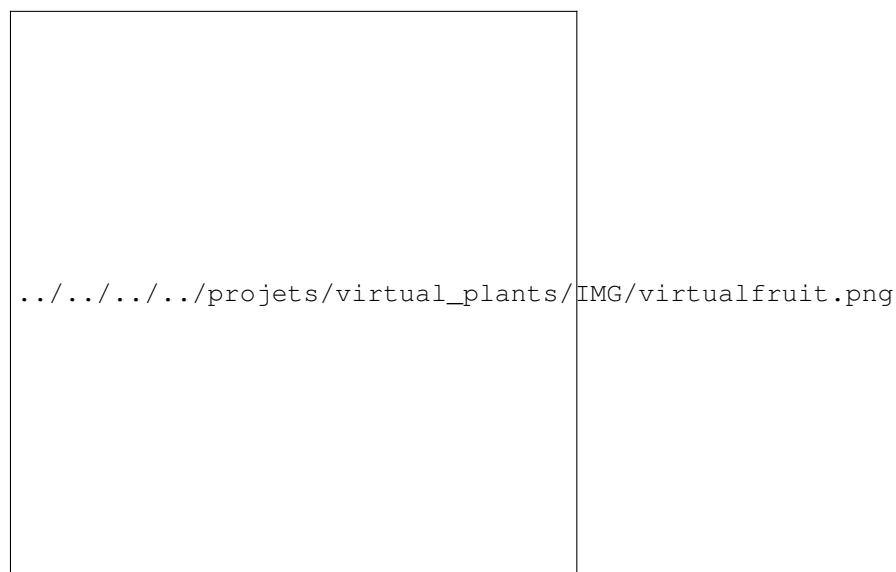


Figure 4. Virtual models of peaches reconstructed from images with simulated vasculatur to simulate carbon and water transport in the fruit

New 2D and 3D root phenotyping platforms are emerging with associated image analysis toolbox (e.g. SmartRoot). The analysis of complex root phenotyping data is thus a new challenge in developmental biology.

We aim at developing a pipeline of methods for analyzing root systems at three scales:

1. tissular scale to identify and characterize the meristem, elongation and mature zones along a root using piecewise heteroscedastic linear models.
2. individual root scale to analyze the dynamics of root elongation
3. root system scale to analyze the branching structure.

This pipeline of analysis methods will be applied to different species (maize, millet and *arabidopsis*) and for different biological objectives (study of genetic diversity for millet and of metabolic and hormonal controls of morphogenesis for maize).

5.3.4. Analyzing shoot and leaf elongation

Participants: Maryline Lièvre, Yann Guédon, Christine Granier [INRA, LEPSE].

This research theme is supported by one PhD programme.

The analysis of phenotyping data coming from automated platforms such as PHENOPSIS often focuses on the growth of a leaf at a given rank along the stem. We aim at developing a pipeline of methods for analyzing the growth of *arabidopsis* shoot at three scales:

1. tissular scale using a probabilistic model of endoreduplication for modeling the distribution of the leaf epidermis cell surfaces. Endoreduplication, which is a replication of the nuclear genome in the absence of cell division that leads to elevated nuclear gene content, strongly affects the leaf epidermis cells of *arabidopsis*.
2. organ scale using nonlinear regression model for analyzing the growth of each successive leaf.

3. shoot scale: The outputs of the analyses at the tissular and organ scales will be summarized as multivariate sequences along the shoots characterizing each successive leaf. These sequences will be augmented by supplementary morphological variables characterizing leaf shape and properties (e.g. presence/absence of trichomes). These sequences will be globally analyzed in order to take into account plant ontogeny and in particular the successive developmental stages before the floral transition for the wild type and selected mutants of *arabidopsis*.

5.3.5. Analyzing perturbations in *Arabidopsis thaliana* phyllotaxis

Participants: Christophe Godin, Yann Guédon, Yassin Refahi, Etienne Farcot, Teva Vernoux, Fabrice Besnard [RDP, ENS].

This research theme is supported by iSAM.

The geometric arrangement of lateral organs along plant stems, named phyllotaxis, shows a variety of striking patterns with remarkable regularities and symmetries. This has interested biologists, physicists, mathematicians and computer scientists for decades. These studies have led to a commonly accepted standard interpretation of phyllotaxis that postulates that organs inhibit the formation of new organs in their vicinity. At a molecular scale, these inhibitory fields have been shown to result from the spatio-temporal distribution of the plant hormone auxin. This model theoretically explains a large part of the diversity of phyllotactic patterns observed in plants.

The cytokinin hormones are known to play a significant role in the regulation of phyllotaxis. Fabrice Besnard and Teva Vernoux realized that *Arabidopsis thaliana* *aahp6* mutants, which are perturbed in the cytokinin signaling pathway, showed unusual chaotic perturbations of the phyllotaxis at macroscopic level.

In order to characterize these perturbations, we designed a pipeline of models and methods which relies on combinatorial and statistical techniques. Using this pipeline of methods, we have shown that the perturbation patterns in both wild-type and mutant plants can be explained by permutations in the order of insertion along the stem of 2 or 3 consecutive organs. The number of successive synchronized organs between two permutations reveals unexpected patterns that depend on the nature of the preceding permutation (2- or 3-permutation). We identified significant individual deviations of the level of baseline segments with reference to 137.5° , which confirms theoretical model predictions. Finally, we highlighted a marked relationship between permutation of organs and defects in the elongation of the internodes in between these organs.

We then looked at the origin of these permutations using confocal microscopy and realized that organs were in fact frequently co-initiated in the mutant, leading after development randomly in half of the cases to permutations. We concluded that the mutant is actually perturbed in the time between consecutive organ initiation (i.e. the plastochrone), while relative angular positions are not affected. After closer inspection, we realized that the mutated gene encodes a protein diffusing from the organs and creating a field around the organs that regulates the plastochrone. We could demonstrate that in the mutant, the absence of this field led to co-initiations and subsequently to the observed permutations.

Altogether, this study sheds a new light on our interpretation of phyllotaxis, revisiting the standard model and suggesting that several fields based on auxin and cytokinin with different properties are required to provide robustness to phyllotaxis. An overview of this work has been published in the journal *Nature* in December online [13]. Methodological developments were published more extensively in [20].

COATI Project-Team

6. New Results

6.1. Network Design and Management

Participants: Julio Araújo, Jean-Claude Bermond, Luca Chiaraviglio, David Coudert, Frédéric Giroire, Alvinice Kodjo, Aurélien Lancin, Remigiusz Modrzejewski, Christelle Molle-Caillouet, Joanna Moulhierac, Nicolas Nisse, Stéphane Pérennes, Truong Khoa Phan, Ronan Pardo Soares, Issam Tahiri.

6.1.1. Optimization in backbone networks

6.1.1.1. Shared Risk Link Group

The notion of Shared Risk Link Groups (SRLG) has been introduced to capture survivability issues where some links of a network fail simultaneously. In this context, the diverse routing problem is to find a set of pairwise SRLG-disjoint paths between a given pair of end nodes of the network. This problem has been proved NP-complete in general and some polynomial instances have been characterized.

In [33], [32], we investigate the diverse-routing problem in networks where the SRLGs are localized and satisfy the *star property*. This property states that a link may be subject to several SRLGs, but all links subject to a given SRLG are incident to a common node. We first provide counterexamples to the polynomial-time algorithm proposed in the literature for computing a pair of SRLG-disjoint paths in networks with SRLGs satisfying the star property, and then prove that this problem is in fact NP-complete. We have also characterized instances that can be solved in polynomial time or are fixed parameter tractable, in particular when the number of SRLGs is constant, the maximum degree of the vertices is at most 4, and when the network is a directed acyclic graph. Moreover, we have considered the problem of finding the maximum number of SRLG-disjoint paths in networks with SRLGs satisfying the star property. We have proved that such problem is NP-hard and hard to approximate. Then, we have provided exact and approximation algorithms for relevant subcases.

6.1.1.2. Wavelength assignment in WDM networks

Let \mathcal{P} be a family of directed paths in a directed graph G . The load of an arc is the number of directed paths containing this arc. Let $\pi(G, \mathcal{P})$ be the maximum of the load of all the arcs and let $w(G, \mathcal{P})$ be the minimum number of wavelengths (colours) needed to colour \mathcal{P} in such a way that two directed paths with the same wavelength are arc-disjoint. These two parameters correspond respectively to the clique number and the chromatic number of the associated conflict graph, and $\pi(G, \mathcal{P}) \leq w(G, \mathcal{P})$. It was known that there exists directed acyclic graphs (DAGs) such that the ratio between $w(G, \mathcal{P})$ and $\pi(G, \mathcal{P})$ is arbitrarily large. In [18], solving a conjecture of an earlier article, we show that the same is true for a very restricted class of DAGs, the UPP-DAGs, those for which there is at most one directed path from a vertex to another. We also characterized the DAGs such that $\pi(G, \mathcal{P}) = w(G, \mathcal{P})$ for all families of directed paths.

6.1.1.3. Multi-operators microwave backhaul networks

In [35], we consider the problem of sharing the infrastructure of a backhaul network for routing. We investigate on the revenue maximization problem for the physical network operator (PNO) when subject to stochastic traffic requirements of multiple virtual network operators (VNO) and prescribed service level agreements (SLA). We use robust optimization to study the tradeoff between revenue maximization and the allowed level of uncertainty in the traffic demands. This mixed integer linear programming model takes into account end-to-end traffic delays as example of quality-of-service requirement in a SLA. To show the effectiveness of our model, we present a study on the price of robustness, i.e. the additional price to pay in order to obtain a feasible solution for the robust scheme, on realistic scenarios.

6.1.2. Energy efficiency

With one third of the world population online in 2013 and an international Internet bandwidth multiplied by more than eight since 2006, the ICT sector is a non-negligible contributor of worldwide greenhouse gases emissions and power consumption. Indeed, power consumption of telecommunication networks has become a major concern for all the actors of the domain, and efforts are made to reduce their impact on the overall figure of ICTs, and to support its foreseen growth in a sustainable way. In this context, the contributors of the European Network of Excellence TREND have developed innovative solutions to improve the energy efficiency of optical networks summarized in [45].

6.1.2.1. Energy aware routing with redundancy elimination

Many studies have shown that energy-aware routing (EAR) can significantly reduce energy consumption of a backbone network. Redundancy Elimination (RE) techniques provide a complementary approach to reduce the amount of traffic in the network. In particular, the GreenRE model combines both techniques, offering potentially significant energy savings.

In [44], we enhance the MIP formulation proposed in [75] for the GreenRE model. We derive cutting planes, extending the well-known cutset inequalities, and report on preliminary computations.

In [37], we propose a concept for respecting uncertain rates of redundant traffic within the GreenRE model, closing the gap between theoretical modeling and drawn-from-life data. To model redundancy rate uncertainty, the robust optimization approach in [73] is adapted and the problem is formally defined as mixed integer linear program. An exemplary evaluation of this concept with real-life traffic traces and estimated fluctuations of data redundancy shows that this closer-to-reality model potentially offers significant energy savings in comparison to GreenRE and EAR.

6.1.2.2. Energy Efficient Content Distribution

The basic protocols of the Internet are point-to-point in nature. However, the traffic is largely broadcasting, with projections stating that as much as 80-90% of it will be video by 2016. This discrepancy leads to an inefficiency, where multiple copies of essentially the same messages travel in parallel through the same links. We have studied approaches to mitigate this inefficiency and reduce the energy consumption of future networks, in particular in [13].

In [29], we study the problem of reducing power consumption in an Internet Service Provider (ISP) network by designing the content distribution infrastructure managed by the operator. We propose an algorithm to optimally decide where to cache the content inside the ISP network. We evaluate our solution over two case studies driven by operators feedback.

Recently, there is a trend to introduce content caches as an inherent capacity of network equipment, with the objective of improving the efficiency of content distribution and reducing network congestion. In [57], [46], [29], we study the impact of using in-network caches and content delivery network (CDN) cooperation on an energy-efficient routing. Experimental results show that by placing a cache on each backbone router to store the most popular content, along with well choosing the best content provider server for each demand to a CDN, we can save up to 23% of power in the backbone.

6.1.3. Distributed systems

6.1.3.1. Distributed Storage systems.

In a P2P storage system using erasure codes, a data block is encoded in many redundancy fragments. These fragments are then sent to distinct peers of the network. In [24], we study the impact of different placement policies of these fragments on the performance of storage systems.

In [39], we propose a new analytical framework that takes into account the correlation between data reconstructions when estimating the repair time and the probability of data loss. The models and schemes proposed are validated by mathematical analysis, extensive set of simulations, and experimentation using the GRID5000 test-bed platform. This new model allows system designers to operate a more accurate choice of system parameters in function of their targeted data durability.

6.1.3.2. P2P Streaming systems

In [41], [68], we propose and analyze a simple localized algorithm to balance a tree. The motivation comes from live distributed streaming systems in which a source diffuses a content to peers via a tree, a node forwarding the data to its children. Such systems are subject to a high churn, peers frequently joining and leaving the system. It is thus crucial to be able to repair the diffusion tree to allow an efficient data distribution. In particular, due to bandwidth limitations, an efficient diffusion tree must ensure that node degrees are bounded. Moreover, to minimize the delay of the streaming, the depth of the diffusion tree must also be controlled. We propose here a simple distributed repair algorithm in which each node carries out local operations based on its degree and on the subtree sizes of its children.

6.1.4. Data Gathering in Radio Networks

We study the problem of gathering information from the nodes of a radio network into a central node. We model the network of possible transmissions by a graph and consider a binary model of interference in which two transmissions interfere if the distance in the graph from the sender of one transmission to the receiver of the other is d_I or less.

In [19], we give an algorithm to construct minimum makespan transmission schedules for data gathering under the following hypotheses: the communication graph G is a tree network, and no buffering is allowed at intermediate nodes and $d_I \geq 2$. In the interesting case in which all nodes in the network have to deliver an arbitrary positive number of packets, we provide a closed formula for the makespan of the optimal gathering schedule. Additionally, we consider the problem of determining the computational complexity of data gathering in general graphs and show that the problem is NP-complete. On the positive side, we design a simple $(1 + 2/d_I)$ -factor approximation algorithm for general networks.

In [59], we focus on the gathering and personalized broadcasting problem in grids. We still consider the non-buffering model. In this setting, though the problem of determining the complexity of computing the optimal makespan in a grid is still open, we present linear (in the number of messages) algorithms that compute schedules for gathering with $d_I = 0, 1, 2$. In particular, we present an algorithm that achieves the optimal makespan up to a small additive constant. Note that, the approximation algorithms that we present also provide approximation up to a ratio 2 for the gathering with buffering. All our results are proved in terms of personalized broadcasting.

In [20], we now allow transmission till a distance d_T and buffering in intermediate nodes. We focus on the specific case where the network is a path with the sink at an end vertex of the path and where the traffic is unitary ($w(u) = 1$ for all u); indeed this simple case appears to be already very difficult. We first give a new lower bound and a protocol with a gathering time that differs only by a constant independent from the length of the path. Then we present a method to construct incremental protocols which are optimal for many values of d_T and d_I (in particular when d_T is prime).

In [50], we focus on gathering uncertain traffic demands in mesh networks with multiple sources and sinks. The scheduling is relaxed into the round weighting problem in which a set of pairwise non-interfering links is called a round, and we seek to successively activate rounds in order to get enough capacity on links to route the demand from the set of sources to the set of sinks. We propose a new robust model considering traffic demand uncertainty, efficiently solved by column generation, and quantify the price of robustness, i.e., the additional cost to pay in order to obtain a feasible solution for the robust scheme.

6.1.5. Routing

6.1.5.1. Routing models evaluation

The Autonomous System (AS)-level topology of the Internet that currently comprises more than 40k ASs, is growing at a rate of about 10% per year. In these conditions, Border Gateway Protocol (BGP), the inter-domain routing protocol of the Internet starts to show its limits, among others in terms of the number of routing table entries it can dynamically process and control. To overcome this challenging situation, the design but also the evaluation of alternative dynamic routing models and their comparison with BGP will be performed by means of simulation. However, existing routing models simulators such as DRMSim, the Dynamic Routing Model

Simulator developed in COATI in collaboration with Alcatel-Lucent [72], are limited in terms of the number of routing table entries they can dynamically process and control on a single computer.

In [63], we have conducted a feasibility study of the extension of DRMSim so as to support the Distributed Parallel Discrete Event paradigm. We have studied several distribution models and their associated communication overhead. We have in particular evaluated the expected additional time required by a distributed simulation of BGP (border gate protocol) on topologies with 100k ASes compared to its sequential simulation. We show that such a distributed simulation of BGP is possible with a reasonable time overhead.

6.1.5.2. Complexity of Shortest Path Routing

In telecommunication networks packets are carried from a source s to a destination t on a path that is determined by the underlying routing protocol. Most routing protocols belong to the class of shortest-path routing protocols. For better protection and efficiency, one wishes to use multiple (shortest) paths between two nodes. Therefore the routing protocol must determine how the traffic from s to t is distributed among the shortest paths. In the protocol called OSPF-ECMP (for Open Shortest Path First-Equal Cost Multiple Path) the traffic incoming at every node is uniformly balanced on all outgoing links that are on shortest paths. In [43], [42], we show that the problem of maximizing even a single commodity flow for the OSPF-ECMP protocol cannot be approximated within any constant factor ratio. Besides this main theorem, we derive some positive results which include polynomial-time approximations and an exponential-time exact algorithm.

6.2. Graph Algorithms

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COATI is also interested in the algorithmic aspects of Graph Theory. In general we try to find the most efficient algorithms to solve various problems of Graph Theory and telecommunication networks. More information on several results presented in this section may be found in R. Soares's thesis [14].

6.2.1. Complexity and Computation of Graph Parameters

We use graph theory to model various network problems. In general we study their complexity and then we investigate the structural properties of graphs that make these problems hard or easy. In particular, we try to find the most efficient algorithms to solve the problems, sometimes focusing on specific graph classes from which the problems are polynomial-time solvable.

6.2.1.1. Parameterized Complexity

Parameterized complexity is a way to deal with intractable computational problems having some parameters that can be relatively small with respect to the input size. This area has been developed extensively during the last decade. More precisely, we consider problems that consist in deciding whether a graph G satisfies some property (i.e., if G belongs to some given family of graphs). For decision problems with input size n and parameter k , the goal is to design an algorithm with running time $f(k).n$, where f depends only on k . Problems for which we can find an optimal algorithm with such time complexity are said to be fixed-parameter tractable (FPT). Equivalently, the goal is to design a polynomial-time algorithm (in k and n) that computes a pair (H, k') where H is a graph (the kernel) with size polynomial in k and $P(G) \leq k$ if and only if $P(H) \leq k'$.

We study the parameterized complexity of the edge-modification problems. Given a graph $G = (V, E)$ and a positive integer k , an edge modification problem for a graph property Π consists in deciding whether there exists a set F of pairs of V of size at most k such that the graph $H = (V, E \Delta F)$ satisfies the property Π . In [25], it is proved that parameterized cograph edge-modification problems have cubic vertex kernels whereas polynomial kernels are unlikely to exist for the P_l -free edge-deletion and the C_l -free edge-deletion problems for $l \geq 7$ and $l \geq 4$ respectively.

We also design a unified parameterized algorithm for computing various widths of graphs (such as branched tree-width, branch-width, cut-width, etc.) [60].

6.2.1.2. Convexity in Graphs

The geodesic convexity of graphs naturally extends the notion of convexity in euclidean metric spaces. A set S of vertices of a graph $G = (V, E)$ is *convex* if any vertex on a shortest path between two vertices of S also belongs to S . The *convex hull* of $S \subset V$ is the smallest convex set containing S . Finally, a *hull set* of a graph is a set of vertices whose convex hull is V . The hull number of a graph G is the minimum size of a hull set in G . In [16], we prove that computing the hull number is NP-complete in bipartite graphs. We also provide bounds and design various polynomial-time algorithms for this problem in different graph classes such as co-bipartite graphs, P_4 -sparse graphs, etc. In [30], we first show a polynomial-time algorithm to compute the hull number of any P_5 -free triangle-free graph. Then, we present four reduction rules based on vertices with the same neighborhood. We use these reduction rules to propose a fixed-parameter tractable algorithm to compute the hull number of any graph G , where the parameter is the size of a vertex cover of G or, more generally, its neighborhood diversity. We also use these reductions to characterize the hull number of the lexicographic product of any two graphs.

6.2.1.3. Hyperbolicity

The Gromov hyperbolicity is an important parameter for analyzing complex networks since it expresses how the metric structure of a network looks like a tree. In other words, it provides bounds on the stretch resulting from the embedding of a network topology into a weighted tree. It is therefore used to provide bounds on the expected stretch of greedy-routing algorithms in Internet-like graphs. However, the best known algorithm for computing this parameter has time complexity in $O(n^{3.69})$, which is prohibitive for large-scale graphs. In [36], we proposed a novel algorithm for determining the hyperbolicity of a graph that is scalable for large graphs. The time complexity of this algorithm is output-sensitive and depends on the shortest-path distances distribution in the graph and on the computed value of the hyperbolicity. Although its worst case time complexity is in $O(n^4)$, it is in practice much faster than previous proposals as it uses bounds to cut the search space. This algorithm allowed us for computing the hyperbolicity of all maps of the Internet provided by CAIDA and DIMES.

6.2.2. Graph searching and applications

Pursuit-evasion encompasses a wide variety of combinatorial problems related to the capture of a fugitive residing in a network by a team of searchers. The goal consists in minimizing the number of searchers required to capture the fugitive in a network and in computing the corresponding capture strategy. We investigated several variants of these games.

6.2.2.1. Variants of graph searching.

We study non-deterministic graph searching where the searchers have to capture an invisible fugitive but can see him a bounded number of times. This variant generalizes the notion of pathwidth and treewidth of graphs. In this setting, we provide a polynomial-time algorithm that approximates the minimum number of searchers needed in trees, up to a factor of two [56].

In [34], [61], we define another variant of graph searching, where searchers have to capture an invisible fugitive with the constraint that no two searchers can occupy the same node simultaneously. This variant seems promising for designing approximation algorithms for computing the pathwidth of graphs. The main contribution in [34], [61] is the characterization of trees where k searchers are necessary and sufficient to win. Our characterization leads to a polynomial-time algorithm to compute the minimum number of searchers needed in trees.

We also study graph searching in directed graphs. We prove that the graph processing variant is monotone which allows us to show its equivalence with a particular digraph decomposition [47].

6.2.2.2. Surveillance Game and Fractional Game.

A surprising application of some variant of pursuit-evasion games is the problem for a web-browser to download documents in advance while an internaut is surfing on the Web. In a previous work, we model this problem as a Pursuit-evasion game called Surveillance game. In [40], [67], we continue our study of the Surveillance game. We provide some bounds on the connected and online variants of this game. In particular,

we show that, in the online variant (when the searchers discover the graph during the game), the best strategy is the trivial one that consists in downloading the document in the neighborhood of the position of the internaut.

In [69], [48], [52], we define a framework generalizing and relaxing many games (including the Surveillance game) where Players use fractions of their token at each turn. We design an algorithm for solving the fractional games. In particular, our algorithm runs in polynomial-time when the length of the game is bounded by 2 (in contrast, computing the surveillance game is NP-hard even when the game is limited to two turns). For some games, we also prove that the fractional variant provides some good approximation. This direction of research seems promising for solving many open problems related to Pursuit-evasion games.

6.2.2.3. Robots in anonymous networks.

Motivated by the understanding of the limits of distributed computing, we consider a recent model of robot-based computing which makes use of identical, memoryless mobile robots placed on nodes of anonymous graphs. The robots operate in Look-Compute-Move cycles that are performed asynchronously for each robot. In particular, we consider various problems such as graph exploration, graph searching and gathering in various graph classes. We provide a new distributed approach which turns out to be very interesting as it neither completely falls into symmetry-breaking nor into symmetry-preserving techniques. We proposed a general approach [38], [66] to solve the three problems in rings even in case of symmetric initial configurations.

6.2.3. Algorithm design in biology

In COATI, we have recently started a collaboration with EPI ABS (Algorithms Biology Structure) from Sophia Antipolis on “minimal connectivity complexes in mass spectrometry based macro-molecular complex reconstruction” [28], [55]. This problem turns out to be a minimum color covering problem (minimum number of colors to cover colored edges with connectivity constraints on the subgraphs induced by the colors) of the edges of a graph, and is surprisingly similar to a capacity maximization problem in a multi-interfaces radio network we were studying.

6.3. Structural Graph Theory

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6.3.1. Graph colouring and applications

Graph colouring is a central problem in graph theory and it has a huge number of applications in various scientific domains (telecommunications, scheduling, bio-informatics, ...). We mainly study graph colouring problems that model resource allocation problems.

6.3.1.1. Backbone colouring

A well-known channel assignment problem is the following: we are given a graph G , whose vertices correspond to transmitters, together with an edge-weighting w . The weight of an edge corresponds to the minimum separation between the channels on its endvertices to avoid interferences. (If there is no edge, no separation is required, the transmitters do not interfere.) We need to assign positive integers (corresponding to channels) to the vertices so that for every edge e the channels assigned to its endvertices differ by at least $w(e)$. The goal is to minimize the largest integer used, which corresponds to minimizing the *span* of the used bandwidth.

We studied a particular, yet quite general, case, called *backbone colouring*, in which there are only two levels of interference. So we are given a graph G and a subgraph H , called *the backbone*. Two adjacent vertices in H must get integers at least q apart, while adjacent vertices in G must get integers at distance at least 1. The minimum span in this case is called the q -backbone chromatic number and is denoted $BBC_q(G, H)$. Backbone forests in planar graphs are of particular interests. In [22], we prove that if G is planar and T is a tree of diameter at most 4, then $BBC_2(G, T) \leq 6$ hence giving an evidence to a conjecture of Broersma et al. [74] stating that the same holds if T has an arbitrary diameter.

6.3.1.2. Weighted colouring

We also studied weighted colouring which models various problems of shared resources allocation. Given a vertex-weighted graph G and a (proper) r -colouring $c = \{C_1, \dots, C_r\}$ of G , the *weight* of a colour class C_i is the maximum weight of a vertex coloured i and the *weight* of c is the sum of the weights of its colour classes. The objective of the Weighted Colouring Problem is, given a vertex-weighted graph G , to determine the minimum weight of a proper colouring of G , that is, its *weighted chromatic number*. In [17], we prove that the Weighted Colouring Problem admits a version of Hajós' Theorem and so we show a necessary and sufficient condition for the weighted chromatic number of a vertex-weighted graph G to be at least k , for any positive real k . The Weighted Colouring Problem remains NP-complete in some particular graph classes as bipartite graphs. In their seminal paper [77], Guan and Zhu asked whether the weighted chromatic number of bounded tree-width graphs (partial k -trees) can be computed in polynomial-time. Surprisingly, the time-complexity of computing this parameter in trees is still open. We show [58] that, assuming the Exponential Time Hypothesis (3-SAT cannot be solved in sub-exponential time), the best algorithm to compute the weighted chromatic number of n -node trees has time-complexity $n^{\Theta(\log n)}$. Our result mainly relies on proving that, when computing an optimal proper weighted colouring of a graph G , it is hard to combine colourings of its connected components, even when G is a forest.

6.3.1.3. On-line colouring

Since many applications, and in particular channel assignment problems, must be solved on-line, we studied on-line colouring algorithms. The most basic and most widespread of them is the greedy algorithm. The largest number of colours that can be given by the greedy algorithm on some graph, is called its *Grundy number* and is denoted $\Gamma(G)$. Trivially $\Gamma(G) \leq \Delta(G) + 1$, where $\Delta(G)$ is the maximum degree of the graph. In [26], we show that deciding if $\Gamma(G) \leq \Delta(G)$ is NP-complete. We then show that deciding if $\Gamma(G) \geq |V(G)| - k$ is fixed-parameter tractable with respect to the parameter k . We also gave similar complexity results on b -colourings, which is a manner of improving colourings on-line.

In [27], we study a game version of greedy colouring. Given a graph G , two players, Alice and Bob, alternate their turns in choosing uncoloured vertices to be coloured. Whenever an uncoloured vertex is chosen, it is coloured by the least positive integer not used by any of its coloured neighbors. Alice's goal is to minimize the total number of colours used in the game, and Bob's goal is to maximize it. The *game Grundy number* of G is the number of colours used in the game when both players use optimal strategies. It is proved in this paper that the maximum game Grundy number of forests is 3, and the game Grundy number of any partial 2-tree is at most 7.

6.3.1.4. Enumerating edge-colourings and total colourings

With the success of moderately exponential algorithms, there is an increasing interest for enumeration problems, because of their own interest but also because they might be crucial to solve optimization problems. In [21], we are interested in computing the number of edge colourings and total colourings of a connected graph. We prove that the maximum number of k -edge-colourings of a connected k -regular graph on n vertices is $k \cdot ((k-1)!)^{n/2}$. Our proof is constructive and leads to a branching algorithm enumerating all the k -edge-colourings of a connected k -regular graph in time $O^*((k-1)!)^{n/2}$ and polynomial space. In particular, we obtain a algorithm to enumerate all the 3-edge-colourings of a connected cubic graph in time $O^*(2^{n/2}) = O^*(1.4143^n)$ and polynomial space. This improves the running time of $O^*(1.5423^n)$ of the algorithm of Golovach et al. [76]. We also show that the number of 4-total-colourings of a connected cubic graph is at most $3 \cdot 2^{3n/2}$. Again, our proof yields a branching algorithm to enumerate all the 4-total-colourings of a connected cubic graph.

6.3.2. Directed graphs

Graph theory can be roughly partitioned into two branches: the areas of undirected graphs and directed graphs (digraphs). Even though both areas have numerous important applications, for various reasons, undirected graphs have been studied much more extensively than directed graphs. One of the reasons is that many problems for digraphs are much more difficult than their analogues for undirected graphs.

6.3.2.1. Finding a subdivision of a digraph

One of the cornerstones of modern (undirected) graph theory is minor theory of Robertson and Seymour. Unfortunately, we cannot expect an equivalent for directed graphs. Minor theory implies in particular that, for any fixed F , detecting a subdivision of a fixed graph F in an input graph G can be performed in polynomial time by the Robertson and Seymour linkage algorithm. In contrast, the analogous subdivision problem for digraph can be either polynomial-time solvable or NP-complete, depending on the fixed digraph F . In a previous paper, we gave a number of examples of polynomial instances, several NP-completeness proofs as well as a number of conjectures and open problems. In [71], we conjecture that, for every integer k greater than 1, the directed cycles of length at least k have the Erdős-Pósa Property : for every n , there exists an integer t_n such that for every digraph D , either D contains n disjoint directed cycles of length at least k , or there is a set T of t_n vertices that meets every directed cycle of length at least k . This generalizes a celebrated result of Reed, Robertson, Seymour and Thomas which is the case $k = 2$ of this conjecture. We prove the conjecture for $k = 3$. We also show that the directed k -Linkage problem is polynomial-time solvable for digraphs with circumference at most 2. From these two results, we deduce that if F is the disjoint union of directed cycles of length at most 3, then one can decide in polynomial time if a digraph contains a subdivision of F .

6.3.2.2. Oriented trees in digraphs

Let $f(k)$ be the smallest integer such that every $f(k)$ -chromatic digraph contains every oriented tree of order k . Burr proved $f(k) \leq (k-1)^2$ in general, and he conjectured $f(k) = 2k - 2$. Burr also proved that every $(8k-7)$ -chromatic digraph contains every antidirected tree. We improve both of Burr's bounds. We show [15] that $f(k) \leq k^2/2 - k/2 + 1$ and that every antidirected tree of order k is contained in every $(5k-9)$ -chromatic digraph. We also make a conjecture that explains why antidirected trees are easier to handle. It states that if $|E(D)| > (k-2)|V(D)|$, then the digraph D contains every antidirected tree of order k . This is a common strengthening of both Burr's conjecture for antidirected trees and the celebrated Erdős-Sós Conjecture. The analogue of our conjecture for general trees is false, no matter what function $f(k)$ is used in place of $k-2$. We prove our conjecture for antidirected trees of diameter 3 and present some other evidence for it. Along the way, we show that every acyclic k -chromatic digraph contains every oriented tree of order k and suggest a number of approaches for making further progress on Burr's conjecture.

DIANA Team

6. New Results

6.1. Service Transparency

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The Complete Picture of the Twitter Social Graph

We made an in-depth study of the macroscopic structure of the Twitter social graph unveiling the highways on which tweets propagate, the specific user activity associated with each component of this macroscopic structure, and the evolution of this macroscopic structure with time for the past 6 years. For this study, we crawled Twitter to retrieve all accounts and all social relationships (follow links) among accounts; the crawl completed in July 2012 with 505 million accounts interconnected by 23 billion links. Then, we presented a methodology to unveil the macroscopic structure of the Twitter social graph. This macroscopic structure consists of 8 components defined by their connectivity characteristics. Each component group users with a specific usage of Twitter. For instance, we identified components gathering together spammers, or celebrities. Finally, we introduced a method to approximate the macroscopic structure of the Twitter social graph in the past, validate this method using old datasets, and discuss the evolution of the macroscopic structure of the Twitter social graph during the past 6 years. This work is accepted in Sigmetrics' 14 [23].

Meddle: Middleboxes for Increased Transparency and Control of Mobile Traffic

Meddle is a platform that relies on traffic indirection to diagnose mobile Internet traffic. Meddle is motivated by the absence of built-in support from ISPs and mobile OSEs to freely monitor and control mobile Internet traffic; the restrictions imposed by mobile OSEs and ISPs also make existing approaches impractical. Meddle overcomes these hurdles by relying on the native support for traffic indirection by mobile OSEs. Specifically, Meddle proxies mobile Internet traffic through a software defined middleboxes configured for mobile traffic diagnosis. We use Meddle to test the limits of the network perspective of mobile Internet traffic offered by traffic indirection. We use this perspective to characterize and control the behavior of mobile applications and provide a first look at ISP interference on mobile Internet traffic. We then performed controlled experiments on 100 popular iOS and Android applications to show how Meddle can be used to identify misbehavior and to block traffic causing this misbehavior. Unlike existing solutions, this activity can be performed without warranty voiding the device and activated on the fly on-demand. This work is done in the context of Aswhin Rao's PhD thesis [11] in collaboration with Northeastern University and Berkeley.

Understanding of modern web traffic

This recent years and with the advent of mobile devices, web traffic has changed and moved from static to dynamic generation. Interestingly, while it is well known that network protocols are intertwined in such a way the characteristics of a layer are affected by those of other layers, most of the measurement work done so far does not pay enough attention to this aspect. We then conducted a cross-layer measurement analysis that confronts all the layers from the very deep technological details to the very high level of users behaviors to shed new light on this issue. To support our study, we analysed an Internet packet traffic trace and showed how this cross-layer analysis approach can explain why TCP flows in mobile traffic are larger than usual. We are currently refining our study to characterises the discrepancies between the different network stack protocol implementations based on the mobile/non-mobile nature of the devices but also their operating system and version. This work is currently under submission.

Checking Traffic Differentiation at the Internet Access

In the last few years, ISPs have been reported to discriminate against specific user traffic, especially if generated by bandwidth-hungry applications. The so-called network neutrality, advocating that an ISP should treat all incoming packets equally, has been a hot topic ever since. We propose Chkdif, a novel method to detect network neutrality violations that takes a radically different approach from existing work: it aims at both application and differentiation technique agnosticism. We achieve this in three steps. Firstly, we perform measurements with the user's real traffic instead of using specific application traces. Secondly, we do assume that discrimination can take place on any particular packet field, which requires us to preserve the integrity of all the traffic we intend to test. Thirdly, we detect differentiation by comparing the performance of a traffic flow against that of all other traffic flows from the same user, considered as a whole. Chkdif performance strongly depends on the way routers reply to probe packets. We carried out large scale experiments to understand the way routers reply to our probes and we calibrated models to these replies. The next step will be to evaluate the performance of Chkdif under these models, before making the tool public and available to the community. Chkdif is currently the subject of a collaboration with I3S around the PhD thesis of Riccardo Ravaioli (funded by the Labex UCN@Sophia). The work is ongoing and will be submitted soon.

Lightweight Enhanced Monitoring for High-Speed Networks

Within the collaboration with Politecnico di Bari, we worked on LEMON, a lightweight enhanced monitoring algorithm based on packet sampling. This solution targets a pre-assigned accuracy on bitrate estimates, for each monitored flow at a router interface. To this end, LEMON takes into account some basic properties of the flows, which can be easily inferred from a sampled stream, and exploits them to dynamically adapt the monitoring time-window on a per-flow basis. Its effectiveness is tested using real packet traces. Experimental results show that LEMON is able to finely tune, in real-time, the monitoring window associated to each flow and its communication overhead can be kept low enough by choosing an appropriate aggregation policy in message exporting. Moreover, compared to a classic fixed-scale monitoring approach, it is able to better satisfy the accuracy requirements of bitrate estimates. Finally, LEMON incurs a low processing overhead, which can be easily sustained by currently deployed routers, such as a CISCO 12000 device. This work has been published in [18].

Packet Extraction Tool for Large Volume Network Traces

Network packet tracing has been used for many different purposes during the last few decades, such as network software debugging, networking performance analysis, forensic investigation, and so on. Meanwhile, the size of packet traces becomes larger, as the speed of network rapidly increases. Thus, to handle huge amounts of traces, we need not only more hardware resources, but also efficient software tools. However, traditional tools are inefficient at dealing with such big packet traces. We proposed pcapWT, an efficient packet extraction tool for large traces. PcapWT provides fast packet lookup by indexing an original trace using a Wavelet Tree structure. In addition, pcapWT supports multi-threading for avoiding synchronous I/O and blocking system calls used for file processing, and is particularly efficient on machines with SSD. PcapWT shows remarkable performance enhancements in comparison with traditional tools such as tcpdump and most recent tools such as pcapIndex in terms of index data size and packet extraction time. Our benchmark using large and complex traces shows that pcapWT reduces the index data size down below 1% of the volume of the original traces. Moreover, packet extraction performance is 20% better than with pcapIndex. Furthermore, when a small amount of packets are retrieved, pcapWT is hundreds of times faster than tcpdump. These results, done in collaboration within the CIRIC, have just been submitted to Computer Networks[34].

Impact of new transport protocols on BitTorrent performance

In the paper [27], we address the trade-off between the data plane efficiency and the control plane timeliness for the BitTorrent performance. We argue that loss-based congestion control protocols can fill large buffers, leading to a higher end-to-end delay, unlike low-priority or delay-based congestion control protocols. We perform experiments for both the uTorrent and mainline BitTorrent clients,

and we study the impact of uTP (a novel transport protocol proposed by BitTorrent) and several TCP congestion control algorithms (Cubic, New Reno, LP, Vegas and Nice) on the download completion time. Briefly, in case peers in the swarm all use the same congestion control algorithm, we observe that the specific algorithm has only a limited impact on the swarm performance. Conversely, when a mix of TCP congestion control algorithms coexists, peers employing a delay-based low-priority algorithm exhibit shorter completion time.

6.2. Open Network Architecture

Participants: Bruno Astuto Arouche Nunes, Chadi Barakat, Daniel Camara, Walid Dabbous, Lucia Guev-geozian Odizzio, Young-Hwan Kim, Mohamed Amine Larabi, Arnaud Legout, Emilio Mancini, Xuan-Nam Nguyen, Thierry Parmentelat, Alina Quereilhac, Damien Saucez, Julien Tribino, Thierry Turletti, Frédéric Urbani.

Delay Tolerant Networks

Delay Tolerant Networks (DTNs) stand for wireless networks where disconnections may occur frequently. In order to achieve data delivery in such challenging environments, researchers have proposed the use of store-carry-and-forward protocols: there, a node may store a message in its buffer and carry it along for long periods of time, until an appropriate forwarding opportunity arises. Multiple message replicas are often propagated to increase delivery probability. This combination of long-term storage and replication imposes a high storage and bandwidth overhead. Thus, efficient scheduling and drop policies are necessary to: (i) decide on the order by which messages should be replicated when contact durations are limited, and (ii) which messages should be discarded when nodes' buffers operate close to their capacity. We worked on a content-centric dissemination algorithm for delay-tolerant networks, called for short CEDO, that distributes content to multiple receivers over a DTN. CEDO assigns a utility to each content item published in the network; this value gauges the contribution of a single content replica to the network's overall delivery-rate. CEDO performs buffer management by first calculating the delivery-rate utility of each cached content-replica and then discarding the least-useful item. When an application requests content, the node supporting the application will look for the content in its cache. It will immediately deliver it to the application if the content is stored in memory. In case the request cannot be satisfied immediately, the node will store the pending request in a table. When the node meets another device, it will send the list of all pending requests to its peer; the peer device will try to satisfy this list by sending the requester all the matching content stored in its own buffer. A meeting between a pair of devices might not last long enough for all requested content to be sent. We address this problem by sequencing transmissions of data in order of decreasing delivery-rate utility. A content item with few replicas in the network has a high delivery rate utility; these items must be transmitted first to avoid degrading the content delivery-rate metric. The node delivers the requested content to the application as soon as it receives it in its buffer. We implemented CEDO over the CCNx protocol, which provides the basic tools for requesting, storing, and forwarding content. Detailed information on CEDO and the implementation work carried out herein can be found in this publication [22] and at the following web page: <http://planete.inria.fr/Software/CEDO/>.

Predicting nodes spatial node density in mobile ad-hoc networks

User mobility is of critical importance when designing mobile networks. In particular, "waypoint" mobility has been widely used as a simple way to describe how humans move. This paper introduces the first modeling framework to model waypoint-based mobility. The proposed framework is simple, yet general enough to model any waypoint-based mobility regimes. It employs first order ordinary differential equations to model the spatial density of participating nodes as a function of (1) the probability of moving between two locations within the geographic region under consideration, and (2) the rate at which nodes leave their current location. We validate our models against real user mobility recorded in GPS traces collected in three different scenarios. Moreover, we show that our modeling framework can be used to analyze the steady-state behavior of spatial node density resulting from a number of synthetic waypoint-based mobility regimes, including the widely used

Random Waypoint (RWP) model. Another contribution of the proposed framework is to show that using the well-known preferential attachment principle to model human mobility exhibits behavior similar to random mobility, where the original spatial node density distribution is not preserved. Finally, as an example application of our framework, we discuss using it to generate steady-state node density distributions to prime mobile network simulations. This work was done in collaboration with Dr. Katia Obraczka, from UC Santa Cruz, and was published in WINET [12].

Software Defined Networking in Heterogeneous Networked Environments

We worked on the exploration of the software defined networking paradigm to facilitate the implementation and large scale deployment of new network protocols and services in heterogeneous networked environments. Our activities related to this research thrust are described hereafter. We wrote a survey of the emerging field of Software-Defined Networking (SDN). SDN is currently attracting significant attention from both academia and industry. Its field is quite recent, yet growing at a very fast pace. Still, there are important research challenges to be addressed. We look at the history of programmable networks, from early ideas until recent developments. In particular we described the SDN architecture in detail as well as the OpenFlow standard. We presented current SDN implementations and testing platforms and examined network services and applications that have been developed based on the SDN paradigm. We concluded with a discussion of future directions enabled by SDN ranging from support for heterogeneous networks to Information Centric Networking (ICN). The survey will be published in 2014 in the IEEE Surveys and Tutorials journal [32].

We have also specified a number of use cases motivating the need for extending the SDN model to heterogeneous networked environments. Such environments consist of infrastructure-based and infrastructure-less networks. These specifications and use cases were summarized in a recent publication [19].

We have also implemented a Capacity Sharing platform by leveraging SDN in hybrid networked environments, i.e., environments that consist of infrastructure-based as well as infrastructureless networks. The proposed SDN-based framework provides flexible, efficient, and secure capacity sharing solutions in a variety of hybrid network scenarios. In the paper published at the Capacity Sharing Workshop CSWS 2013 [40], we identify the challenges raised by capacity sharing in hybrid networks, describe our framework in detail and how it addresses these challenges, and discuss implementation issues.

The aforementioned capacity sharing work is just one application and a preliminary of our longer term effort. We have also started to specify the H-SDN protocols based on the use cases mentioned above, including the capacity sharing use case. These efforts are part of a broader work where we propose a framework to enable the implementation and deployment of more generic H-SDN networks and applications. This framework contemplates important issues regarding H-SDN deployment, such as: security, increased scalability and performance by distribution of SDN control and seamless handover of mobile stations, to name a few. We have targeted Mobisys2014 as a venue for publishing our proposal and results regarding this topic [39].

Rule Placement in Software-Defined Networking

OpenFlow is a new communication standard that decouples control and data planes to simplify traffic management. More precisely, OpenFlow switches populate their forwarding tables by opportunistically querying a centralized controller for flows whose rules (i.e., forwarding actions) are not yet installed. However, the flexibility offered by this new paradigm comes at the expense of extra signaling overhead as, in practice, switches might not be able to store all rules in their local forwarding tables. The question of which rules to install then becomes essential. In our research, we leverage the fact that some flows are more important to manage than others, and thus construct an optimal placement problem of rules in OpenFlow switches that ensures the most valuable traffic is matched by its appropriate rules while respecting switches and links capacity constraints. The rest of the traffic with no installed rules follows a default, yet less appropriate, path within the network. We have

formulated and solved this optimisation problem in the case of realistic operational needs, and prove that the optimal placement of rules is NP-hard. The intrinsic complexity of the problem led us to design a greedy heuristic that we evaluated with two representative use cases: BGP multihoming and Access Control Lists. On one hand, the evaluation shows the versatility and the generality of the optimization problem, and on another hand, it demonstrates that heuristics with apparent simplicity are still efficient. We are now extending this work to support traffic dynamics and mobility. This work is currently under submission.

Information-Centric Networking and economical aspects

With the explosion of broadband Over-The-Top (OTT) services all around the world, the Internet is autonomously migrating toward overlay and incrementally deployable content distribution infrastructures. Information-Centric Networking (ICN) technologies are the natural candidates to more efficiently bind and distribute popular contents to users. However, the strategic incentives in exploiting ICN, for both users and ISPs, are much less understood to date. In this work, we shed light on how OTTs shall shape prices and discounts to motivate ICN usage, depending on their awareness over content distribution costs. Actually, the Internet ecosystem is fast and dynamic and new ideas can rapidly reach millions of users spread worldwide without having to rely on special involvement of intermediate transit networks. In this context, Over-The-Top broadband content providers can leverage their customer resources to allowing, from one hand, to improve access performance, and, from the other hand, to reduce operational costs the OTT provider would incur on by directly serving the customers. In this context, Information-Centric Networking appears as an adequate offloading technique, if incrementally deployed as an overlay network. This paper analyses the incentive compatibility in the adoption of a ICN overlay for OTT services and is, as of our knowledge, we are the first in addressing the topic by following a non-cooperative game theory reasoning, we believe adequate in its non-cooperative nature due to independency between the involved ICN stakeholders. Our analysis allows us to assess that the business model currently standing for legacy CDNs does not make strategic sense for ICN overlays and that, however, it exists incentives for OTT customers to get involved in the distributions process via an ICN overlay reducing so server load. These unique specifications for the design of an ICN overlay for OTT content distribution do also have relevant implications for ICN protocol design. The OTT provider would need a form of control over the ICN overlay operations. We identify the usage of a OTT- set policy metric for ICN routing as the most appropriate way to ensure ICN users follow the equilibrium strategy suggested by our incentive compatibility framework. We highlight moreover the need of a scalable way of building and controlling ICN overlays over the legacy TCP/IP Internet to support related signaling, forwarding rule registration, and positive strategic behaviour.

Information-Centric Networking and rate control implications

Information-centric networking (ICN) leverages content demand redundancy and proposes in-network caching to reduce network and servers load and to improve quality of experience. We have studied the interaction between in-network caching of ICN and Additive Increase Multiplicative Decrease (AIMD) end-to-end congestion control with a focus on how bandwidth is shared, as a function of content popularity and caches provisioning. As caching shortens AIMD feedback loop, the download rate of AIMD is impacted. We earlier shed light on the potential negative impact of in-network caching on instantaneous throughput fairness. The work accomplished in 2013 precisely quantify the issue thanks to an analytic model based on Discriminatory Processor Sharing and real experiments, we observe that popular contents benefit from caching and realize shorter download times at the expense of unpopular contents which see their download times inflated by a factor bounded by $\frac{1}{1-\rho}$, where ρ is the network load. This bias can be removed by redefining congestion control to be delay independent or by over-provisioning link capacity at the edge so that to compensate for the greediness of popular contents. The experimentation study has been supported by the work of Ilaria Cianci internship on the CCN-Jocker emulator. This work is currently under submission.

Routing in Information-Centric Network

The idea behind Information-Centric Networking (ICN) is to omit the notion of host and location and use contents as direct routing and forwarding primitives, instead of IP addresses. This shift of paradigm allow ICN to natively offer in-network caching, i.e., to cache content on the path from content providers to requesters. Actually our studies shows a large spatial and temporal locality of contents amongst users in the same network which proves that in-network caching can achieve good overall performance. However, caching contents strictly on their paths is far from being optimal when paths are not shared among content consumers as contents may be replicated on routers so reducing the total volume of contents that can be cached. To overcome this limitation, we introduced the notion of off-path caching in [21] where we allocate content to well defined off-path caches within the network and deflect the traffic off the optimal path toward these caches that are spread across the network. Off-path caching improves the global hit ratio by efficiently utilizing the network-wide available caching capacity and permits to reduce egress links bandwidth usage.

Locator/Identifier Separation Protocol (LISP)

The future Internet has been a hot topic during the past decade and many approaches proposed towards this future Internet, ranging from incremental evolution to complete clean state ones, have been proposed. One of the proposition, LISP, advocates for the separation of the identifier and the locator roles of IP addresses to reduce BGP churn and BGP table size. Up to now, however, most studies concerning LISP have been theoretical and, in fact, little is known about the actual LISP deployment performance. We filled this gap through measurement campaigns carried out on the LISP Beta Network. More precisely, we evaluated the performance of the two key components of the infrastructure: the control plane (i.e., the mapping system) and the interworking (i.e., communication between LISP and non-LISP sites). Our measurements highlight that performance offered by the LISP interworking infrastructure is strongly dependent on BGP routing policies. If we exclude misconfigured nodes, the mapping system typically provides reliable performance and relatively low median mapping resolution delays. Although the bias is not very important, control plane performance favours USA sites as a result of its larger LISP user base but also because European infrastructure is unreliable. Finally, the LISP Map-versioning RFC mentioned in the last year activity report was published this year [33]. All details are reported in [17], [29].

Running Live CCNx Experiments on Wireless and Wired Testbeds with NEPI

CCNx has long left the early development stage where simulation and emulation frameworks, like ccnSim and mininet, were enough to validate new approaches and improvements. It has now reached a level of maturity which calls for evaluation in more realistic environments. If it is to be deployed in the wild Internet or even in private network settings, a framework that provides proper validation in comparable environments is required. For this purpose we demonstrate the capabilities of the NEPI framework to run CCNx experiments in realistic environments. NEPI can run CCNx experiments directly on Internet settings as well as wireless or wired private network environments. This framework allows to automate host configuration, software installation, result collection and to define execution sequence between applications. Furthermore, it provides the ability to conduct interactive experiments where researchers are free to modify the experiment scenario on the fly. These results were demonstrated at CCNxCon'2013 [38].

Evaluating costs of CCN overlays

We are currently involved in a collaboration with PARC (Palo Alto research center) regarding the evaluation of the CCN (Control Centric Networking) technology. Early results of this work were presented in the poster session at the CCNxConf 2013 meeting. In this work we present a set of scenarios to evaluate the performance of CCN overlays on top of the Internet, for worse case conditions. We used the NEPI experiment API to construct different overlay topologies on PlanetLab, for which we varied the topology configuration (e.g. number and degree of nodes), the CCN parameters (e.g. pipeline, cache usage, prefix routes) and the traffic patterns (e.g. single stream, prefix independent chunks). The objective of this study is to find correlations between these variables and the time to deliver content and the overlay network utilization. Our contribution is twofold. In one hand we provide a benchmark which can be used as reference for comparison of new CCNx

versions and for other ICN solutions, and as input traces for CCN simulations. In the other hand, we provide results that can be used to improve the CCNx implementation and that can help Internet providers or end users to better design CCN overlays to satisfy their needs. The work is still ongoing and will be submitted soon.

Enabling Iterative Development and Reproducible Evaluation of Network Protocols

Over the last two decades several efforts have been made to provide adequate experimental environments, aiming to ease the development of new network protocols and applications. These environments range from network simulators providing highly controllable evaluation conditions, to live testbeds providing realistic evaluation environment. While these different approaches foster network development in different ways, there is no simple way to gradually transit from one to another, or to combine their strengths to suit particular evaluation needs. We believe that enabling a gradual transition from a pure simulated environment to a pure realistic one, where the researcher can decide which aspects of the environment are realistic and which are controllable, allows improving network solutions by simplifying the problem analysis and resolution. We have designed a new network experimentation framework, called IDEV, where simulated and real components can be arbitrarily combined to build custom test environments, allowing refining and improving new protocols and applications implementations by gradually increasing the level of realism of the evaluation environment. Moreover, we proposed a testbed architecture specifically adapted to support the proposed concept, and discuss the design choices we made based on our previous experience in the area of network testbeds. These choices address key issues in network testbed development, such as ease of experimentation, experiment reproducibility, and testbed federation, to enable scaling the size of experiments beyond what a single testbed would allow. This work has been described in a paper that will be published in the Computer Networks journal in 2014, see [15].

Direct Code Execution: Revisiting Library OS Architecture for Reproducible Network Experiments

We proposed Direct Code Execution (DCE), a framework that dramatically increases the number of available protocol models and realism available for ns-3 simulations. DCE meets the goals recently proposed for fully reproducible networking research and runnable papers, with the added benefits of 1) the ability of completely deterministic reproducibility, 2) the scalability that simulation time dilation offers, 3) capabilities supporting automated code coverage analysis, and 4) improved debuggability via execution within a single address space. We reported on packet processing benchmark and showcased key features of the framework with different use cases. Then, we reproduced a previously published Multipath TCP (MPTCP) experiment and highlight how code coverage testing can be automated by showing results achieving 55-86% coverage of the MPTCP implementation. We also demonstrated how network stack debugging can be easily performed and reproduced across a distributed system. Our first benchmarks are promising and we believe this framework can benefit the network community by enabling realistic, reproducible experiments and runnable papers. This work has been published in the ACM CoNext conference 2013 [25], in Santa Barbara, CA, USA and will be published in IEEE Communication Magazine in 2014 [14]. DCE has been demonstrated at the ACM MSWiM conference at Barcelona, Spain in November 2013 [42]. In the same context, we designed DCE Cradle, a framework that allows to use any features of the Linux kernel network stack with existing ns-3 applications. DCE Cradle uses DCE to address the brittleness of Network Simulation Cradle (NSC). We carefully designed DCE Cradle without breaking the existing functionality of DCE and ns-3 socket architecture by considering the gaps between the asynchronous ns-3 socket API and the general POSIX socket API. We validated the implementation of DCE Cradle with the behavior of TCP implementation in congested links, and then studied its performance by focusing on the simulation time and network scale. We showed that DCE Cradle is at most 1.3 times faster than NSC, while it is about 2.2 times slower than the ns-3 native stack. Then we showcased an actual implementation of the DCCP transport protocol to verify how easy it is to simulate a real implementation using DCE Cradle. We believe that this tool can highly benefit the network community by enabling more realistic evaluation of network

protocols. This work has been published in the ns-3 workshop in 2013 in Cannes and got the best paper award [26].

The ns-3 Consortium

We have founded in 2012 a consortium between Inria and University of Washington. The goals of this consortium are to (1) provide a point of contact between industrial members and the ns-3 project, to enable them to provide suggestions and feedback about technical aspects, (2) guarantee maintenance of ns-3's core, organize public events in relation to ns-3, such as users' day and workshops and (3) provide a public face that is not directly a part of Inria or NSF by managing the <http://www.nsnam.org> web site. The Consortium started his activities in March 2013. Two European institutions (Centre Tecnològic de Telecomunicacions de Catalunya - CTTC and INESC Porto)) and two American universities (Georgia Tech and Bucknell) joined the consortium as Executive members in 2013. For more details see the consortium web page <https://www.nsnam.org/consortium/>.

Contiki over ns-3

This year we worked on the adaptation of Contiki OS over ns-3. Contiki is a popular, and highly optimized, operating system for sensor nodes. We developed a proof of concept adaptation layer that, even though simple and limited, was able to show that such interaction is indeed possible. The adaptation layer was capable of transferring data from different sensors using ns-3 to interconnect them. Sensor nodes were controlled by the ns-3 scheduler, respecting the ns-3 clock and executing over simulated time. In fact, the sensors were not even aware they were placed over a simulated network.

Federation of experimental testbeds

We are involved in the F-Lab (French ANR) project, the FED4FIRE (E.U. IP) project and have the lead of the "Control Plane Extensions" WorkPackage of OpenLab (E.U. IP) project. Within these frameworks, as part of the co-development agreement between the DIANA team and Princeton University, we kept contributing into one of the most visible and renown implementations of the Testbed-Federation architecture known as SFA for Slice-based Federation Architecture. As a sequel of former activities we also keep a low-noise maintenance activity of the PlanetLab software, which has been running in particular on the PlanetLab global testbed since 2004, with an ad-hoc federated model in place between PlanetLab Central (hosted by Princeton University) and PlanetLab Europe (hosted at Inria) since 2007. During 2013, as a step forward to our contribution to the specification of the Aggregate Manager (AM) API v3, which is the control plane interface through which experimenters discover and reserve resources at testbeds, we have focused on coming up with a separate implementation of SFAWrap that supports AM API v3 and brings a more elaborate lifecycle for slices provisioning. Secondly, we implemented a AM API v2 to AM API v3 adapter, which represents the glue between the already existing AM API v2 compliant testbed drivers and the AM API v3 compliant interfaces of SFAWrap. The v2 to v3 adapter provides AM API v3 compatibility to already existing AM API v2-based testbed drivers until their authors find the time to adapt their driver for a native support of AM API v3 if they want to take full advantage of the new lifecycle. Thirdly, within the contexts of the formerly listed projects, and as a consequence of the growing need for testbeds federation, the providers of testbeds such as: BoneFire, SmartSantander decided to adopt SFAWrap in order to join the global federation of testbeds by exposing their testbeds through SFA. Thus, we had to provide to those partners a close support to achieve this goal. Finally, as for any kind of software development project, and due to the growing usage of SFAWrap, we had to be active on both operational and maintenance tasks. See [37] and [41] for more details. We also contributed, in the context of the Fed4FIRE project, to the definition and early implementation of an architecture for heterogeneous federation of future internet experimental facilities. The results of this work were presented at the FutureNetworkSummit 2013 conference. In this work, requirements involving different aspects of the federation of heterogeneous facilities were collected and analysed, and a multilayer architecture was proposed to address them. Our contribution mainly focuses on the experiment control plane of the federation architecture [28]. The experiment control plane involves the interface between the experimenter and the facilities, and

it covers tasks such as federation of the resource discovery, provisioning, reservation, configuration and deployment. The proposed architecture combines the use of SFA (Slice Federation Architecture) and OMF (cOntrol and Management Framework) into a common middle-ware that allows to federate resource control within an experiment across facilities.

FOCUS Project-Team

6. New Results

6.1. Service-oriented computing

Participants: Mario Bravetti, Ivan Lanese, Fabrizio Montesi, Gianluigi Zavattaro.

6.1.1. Primitives

We have studied primitives used in the context of service-oriented computing, at different levels of abstraction and in different contexts. At the abstract level, we considered both standard web services and Internet of Things, where computational and communication capabilities are attached to real-world objects such as smartphones or alarm clocks. For web services, we defined SSCC (Stream-based Service-Centered Calculus) [17], a calculus allowing to describe both service composition (orchestration) via streams and the protocols that services follow when invoked (conversation). We assessed the expressive power of SSCC by modeling van der Aalst's workflow patterns and an automotive case study from the European project Sensoria. For analysis, we presented a simple type system ensuring compatibility of client and service protocols. We also studied the behavioral theory of the calculus, highlighting some axioms that capture the behavior of the different primitives. As a final application of the theory, we defined and proved correct some program transformations. For Internet of Things, a main contribution [37] has been the definition of a calculus and of an equivalence allowing to capture the behavior of the system as seen by the human end-user. Since this equivalence is not compositional we defined also a finer equivalence which is compositional. We showed how our equivalences can be applied to reason on simple Internet of Things examples.

At a more concrete level, we have continued to study and extend the Jolie language. In [44] we present a detailed description of the Jolie language. We put our emphasis on how Jolie can deal with heterogeneous services. On the one hand, Jolie combines computation and composition primitives in an intuitive and concise syntax. On the other hand, the behavior and deployment of a Jolie program are orthogonal: they can be independently defined and recombined as long as they have compatible typing. In [42] we extended Jolie to model process-aware web information systems. Our major contribution is to offer a unifying approach for the programming of distributed architectures based on HTTP that support typical features of the process-oriented paradigm, such as structured communication flows and multiparty sessions.

6.1.2. Choreographies

Choreographies are high-level descriptions of distributed interacting systems featuring as basic unit a communication between two participants. A main feature of choreographies is that they are deadlock-free by construction. From a choreography one can automatically derive the behavior of each participant using a notion of projection. Under suitable conditions on the structure of a choreography, the correctness of its projection can be established in terms of a trace-based semantics. In [24] we have proposed a purely-global programming model. The idea is to define abstract choreographies – called protocol specifications – and use them to type a more concrete choreography. This more concrete choreography is used to generate executable code for the different participants. The approach is based on a novel interpretation of asynchrony and parallelism. We evaluated the approach by providing a prototype implementation for a concrete programming language and by applying it to some examples from multicore and service-oriented programming [49]. In [43] we tackled one of the main limitations of choreographies, namely the fact that they model closed systems. To this end we proposed a notion of composable choreographies. The key of our approach is the introduction of partial choreographies, which can mix global descriptions with communications among external peers. We prove that if two choreographies are composable, then the endpoints independently generated from each choreography are also composable, preserving their typability and deadlock-freedom. In [39] we showed how to transform choreographies which do not satisfy the conditions for their projection into choreographies that satisfy them preserving their behavior and enabling a correct projection.

6.2. Models for reliability

Participants: Ivan Lanese, Michael Lienhardt, Gianluigi Zavattaro.

6.2.1. Reversibility

We have continued the study of reversibility started in the past years, aimed at developing programming abstractions for reliable distributed systems. In [38] we present *croll-pi*, a concurrent calculus extending *roll-pi* – an higher-order pi-calculus featuring a rollback operator – allowing the specification of alternatives to a computation to be used upon rollback. Alternatives in *croll-pi* are attached to messages. We show the robustness of this mechanism by encoding more complex idioms for specifying alternatives. We illustrate the expressiveness of our approach by encoding a calculus of communicating transactions and by modeling the 8-queens problem. We also formally prove that *croll-pi* is strictly more expressive than *roll-pi*.

6.2.2. Compensations

We have continued the study of the expressive power of primitives for specifying compensations in long running transactions. Dynamic compensation installation allows for easier specification of fault handling in complex interactive systems since it enables to update the compensation policies according to run-time information. In [40] we show that in a simple pi-like calculus with static compensations the termination of a process is decidable, but it is undecidable in one with dynamic compensations. We then consider three commonly used patterns for dynamic compensations: parallel compensations, where new compensation items can only be added in parallel, replacing compensations, where old compensations are replaced, and nested compensations, where old compensations can be used (linearly) to build new ones. We show that termination is decidable in the first two cases and undecidable in the last one.

6.3. Cloud Computing

Participants: Elena Giachino, Michael Lienhardt, Tudor Alexandru Lascu, Jacopo Mauro, Gianluigi Zavattaro.

6.3.1. Languages for cloud applications

To foster the industrial adoption of virtualized services, it is necessary to address two important problems: (1) the efficient analysis, dynamic composition of services with qualitative and quantitative service levels and (2) the dynamic control of resources such as storage and processing capacities according to the internal policies of the services. Current technologies for cloud computing, addresses these problems at deployment and run time. The ENVISAGE project and the position paper [20] proposes, on the contrary, to overcome these problems by leveraging service-level agreements into software models and resource management into early phases of service design.

6.3.2. Models for cloud application deployment

Cloud computing offers the possibility to build sophisticated software systems on virtualized infrastructures at a fraction of the cost necessary just few years ago, but deploying/maintaining/reconfiguring such software systems is a serious challenge. The AEOLUS project, aims to tackle the scientific problems that need to be solved in order to ease the problem of efficient and cost-effective deployment and administration of the complex distributed architectures which are at the heart of cloud applications [25]. In particular, it is necessary to define appropriate models for the representation of the interdependencies among the software components of a cloud application as well as declarative languages for the specification of the desired application configuration. We have proposed [31] a model for the representation of the component lifecycle and of its dependencies/conflicts with the other components. Based on such model, we have defined a sound and complete algorithm that efficiently computes a deployment plan (i.e. a sequence of low-level component deployment actions) capable of reaching a final configuration including at least some predefined basic components [48] and we have realized a prototypical implementation of such algorithm which was proved to be effective on case-studies of realistic size (i.e. hundreds of components) [41].

6.4. Resource Control

Participants: Michele Alberti, Alberto Cappai, Ugo Dal Lago, Marco Gaboardi, Simone Martini, Paolo Parisen Toldin, Giulio Pellitta, Davide Sangiorgi, Marco Solieri, Valeria Vignudelli.

6.4.1. Expressive type systems for complexity analysis

Along 2013, our work on expressive methodologies for complexity analysis of higher-order languages has proceeded. In particular, we have focused our attention on extending linear dependent types to languages with control operators in the style of `callcc` [27]. This has taken the form of a generalization of bounded linear logic towards Laurent’s polarized linear logic, which is then turned into a type system for the lambda-mu-calculus (in which the aforementioned control operator can indeed be implemented). In the introduced type system, all typable terms can be reduced in polynomial time. We also worked on the linear dependent type inference and on its implementation (though the work has not yet been transferred onto the *Lideal* tool implementing type inference for dependently linear type systems, see <http://lideal.cs.unibo.it/>); more specifically, we showed that type inference can in this context be reduced to a form of constraint amenable to be solved by SMT solvers [28]. Finally, a call-by-value version of *dℓPCF* has been defined and proved sound but also relatively complete as a tool for complexity analysis of programs [16].

6.4.2. Complexity analysis and process algebras

Complexity analysis methodologies drawn from linear logic have been adapted to higher-order process algebras, obtaining linear versions of the higher-order π -calculus in which reduction sequences are guaranteed to have a length bounded by a polynomial [14]. This is done by following the exponential discipline Lafont’s Soft Linear logic suggests.

6.4.3. Characterizing probabilistic complexity classes

We have also been looking [10] (papers extracted from the thesis should appear soon) at probabilistic computation and at whether probabilistic complexity classes like **BPP**, **ZPP** and **PP** can be characterized by logics and λ -calculi. We encountered some problems in doing the above for **BPP** and **ZPP**, which are semantic classes and which, as a consequence, cannot be easily enumerated (and captured by ICC systems). On the other hand, probabilistic classes like **PP** can indeed be characterized by λ -calculi, as shown by our recent work on RSLR, a system derived from Hofmann’s SLR that captures the (deterministic) polytime computable functions.

6.4.4. Ensuring differential privacy

Differential privacy offers a strong guaranteed bound on loss of private information due to release of query results, even under worst-case assumptions. One of the challenges in proving queries differentially private is to prove an upper bound on the query’s sensitivity, i.e., the maximum change in the query’s output that can result from changing the data of a single individual. Reed and Pierce have recently proposed a type analysis using numerical annotations in types to describe bounds on the sensitivity of the queries. A first delicate aspect of this approach is that in order to verify if a program is typable or not one needs to come up with numerical annotations and verify their consistency. Finding a “small” annotation is crucial, since the privacy depends on it. For this reason we designed a sensitivity inference tool [26] that combined with the Z3 SMT solver is able to verify and infer a minimal sensitivity bound in an automatic and efficient way. Another delicate aspect of this approach is the *expressivity* of the type analysis. Reed and Pierce’s type system offers only a very limited form of numerical annotations. These numerical annotations are not enough to provide a bound for programs whose sensitivity depends on data available only at runtime. To recover this problem we introduced *Dfuzz* [32], a language combining linear types and lightweight dependent types.

6.5. Verification of extensional properties

Participants: Ornella Dardha, Elena Giachino, Michael Lienhardt, Cosimo Laneve, Fabrizio Montesi.

Extensional refers to properties that have to do with behavioral descriptions of a system (i.e., how a system looks like from the outside). Examples of such properties include classical functional correctness and deadlock freedom. Most work carried out this year has to do with type systems for concurrent objects and components ensuring safe and reliable interactions, and on deadlock analysis for systems of concurrent objects or within process sessions.

6.5.1. Type systems for objects and components

In previous work, we had developed an integration of session types, for specifying and validating structured communication sequences (sessions) into a class-based core object language for building network applications. We have defined [12] a constraint-based type system that reconstructs the appropriate session types of session declarations instead of assuming that session types are explicitly given by the programmer, and used static analysis via types to ensure that, once a session has started, computation cannot get stuck on a communication deadlock.

In previous papers, we had proposed a component layer for object-oriented language ABS (studied in the EU project Hats), that allows one to perform updates on objects by means of communication ports and their rebinding. We have now [29] introduced a type system for this component model that statically enforces that no object will attempt illegal rebinding.

6.5.2. Deadlock analysis

Deadlock represents an insidious and recurring threat when systems also exhibit a high degree of resource and data sharing. We address deadlock analysis of two such systems: (1) concurrent object-oriented languages; (2) protocol specifications.

For (1), we have developed a framework for statically detecting deadlocks in a concurrent object-oriented language with asynchronous method calls and cooperative scheduling of method activations. Since this language features recursion and dynamic resource creation, deadlock detection is extremely complex and state-of-the-art solutions either give imprecise answers or do not scale. In order to augment precision and scalability we propose a modular framework that allows several techniques to be combined. The basic component of the framework is a front-end inference algorithm that extracts abstract behavioral descriptions of methods, called contracts, which retain resource dependency information [33]. This component is integrated with a number of possible different back-ends that analyze contracts and derive deadlock information. As a proof-of-concept, we discuss two such back-ends: (i) an evaluator that computes a fixpoint semantics [33] and (ii) an evaluator using abstract model checking [34].

For (2), in [24], we develop a typing discipline that verifies choreographies against protocol specifications, based on multiparty sessions. Exploiting the nature of global descriptions, our type system defines a new class of deadlock-free concurrent systems (deadlock-freedom-by-design), provides type inference, and supports session mobility. We give a notion of Endpoint Projection (EPP) which generates correct entity code (as pi-calculus terms) from a choreography. Finally, we evaluate our approach by providing a prototype implementation for a concrete programming language and by applying it to some examples from multicore and service-oriented programming.

Finally, en passant we remind [23], that studies deadlock analysis of concurrent object-oriented languages via encoding into Petri nets, which had already been discussed in last year's report.

6.6. Expressiveness of computational models

Participants: Roberto Amadini, Ornela Dardha, Maurizio Gabbrielli, Daniel Hirschhoff, Jean-Marie Madiot, Jacopo Mauro, Davide Sangiorgi, Gianluigi Zavattaro.

Expressiveness refers to the study of the descriptive power of computational models.

The fusion calculi are a simplification of the π -calculus in which input and output are symmetric and restriction is the only binder. We show [35] a major difference between these calculi and the π -calculus from the point of view of types, proving some impossibility results for subtyping in fusion calculi. We propose a modification of fusion calculi in which the name equivalences produced by fusions are replaced by name preorders, so to be able to import subtype systems, and related results, from the π -calculus. We have studied the consequences of the modification on behavioural equivalence and expressiveness.

In Focus we use notions of constraint to define in a succinct way models of computation and current constraint solving technologies to solve problems modeled using constraints. For this reason we have studied the expressive power of various computational models involving constraints and their practical impact in terms of solving/execution performances. In [18] we have investigated how the notion of constraint augments the expressive power of a concurrent language if priorities are introduced. The chosen language is Constraint Handling Rules, a committed-choice declarative language originally designed for writing constraint solvers and that is nowadays a general purpose language. The result has been obtained by first formalising the meaning of language encodings and language embedding, widely used in concurrency theory. Different ways to model and define disaster scenarios are analyzed and compared in [11], where we study a model expressive enough to define a disaster scenario that, at the same time, can be used to find plans to save the victims of a disaster using modern constraint solving technology. Similarly, different computation models are considered in [22] where we study how machine learning techniques can be used to boost the performances of constraint solvers. A technique dubbed “portfolio approach” is used to combine the different performances of constraint solvers to obtain a globally better solver using, as a starting point, a simple low-level constraint language.

In [30] we propose an integration of structural sub-typing with boolean connectives and semantic sub-typing to define a Java-like programming language that exploits the benefits of both techniques. The resulting language has a more expressive set of types that comes from the use of boolean constructs, negation types, and the integration of structural and nominal sub-typing in an object-oriented setting. By implementing traditional Java-language constructs we show that the proposed language is also expressive enough w.r.t. the Java language.

LOGNET Team

6. New Results

6.1. A Backward-Compatible Protocol for Inter-routing over Heterogeneous Overlay Networks

Participants: Giang Ngo Hoang [contact], Luigi Liquori, Hung Nguyen Chan [VIELINA, Vietnam].



Figure 11. An Overlay Gateway Protocol Topology

Overlay networks are logical networks running on the highest level of the OSI stack: they are applicative networks used by millions of users everyday. In many scenarios, it would be desirable for peers belonging to overlays running different protocols to communicate with each other and exchange certain information. However, due to differences in their respective protocols, this communication is often difficult or even impossible to be achieved efficiently, even if the overlays are sharing common objectives and functionalities. In this paper, we address this problem by presenting a new overlay protocol, called OGP (Overlay Gateway Protocol), allowing different existing networks to route messages between each other in a backward-compatible fashion, by making use of specialized peers joined together into a super-overlay. Experimental results on a large scale Grid5000 infrastructure show that having only a small number of nodes running the OGP protocol is sufficient for achieving efficient routing between heterogeneous overlay networks.

The three scenarios in Figure 11 are shown to illustrate the routing of three lookup queries, in which full OGP peers, lightweight OGP peers and blind peers interact in order to reach across overlays represent requests, while dashed lines represent responses. using the OGP super-overlay. The three smaller ovals represent standard overlays, while the largest oval represents the OGP super-overlay, forwarding messages back and forth between standard overlays. The black squares B; C; G; N and P represent full OGP peers, the black circles A; D and F represent lightweight OGP peers, while the white circles E; H, and M represent blind peers. Solid lines requests, while dashed lines represent responses. The paper is the continuation of the work of HotPost 2011 [7] and Hets-Nets 2012 [8]: it has been also accepted to ACM SAC 2013 [36] and a long version has been accepted to the International Conference ICDCN 2014 [32].

6.2. Interconnection of large scale unstructured P2P networks: modeling and analysis

Participants: Rossano Gaeta [Univ. Turin], Vincenzo Ciancaglini, Riccardo Loti, Luigi Liquori.

Interconnection of multiple P2P networks has recently emerged as a viable solution to increase system reliability and fault-tolerance as well as to increase resource availability. In this paper we consider interconnection of large scale unstructured P2P networks by means of special nodes (called *Synapses*) that are co-located in more than one overlay. Synapses act as *trait d'union* by sending/forwarding a query to all the P2P networks they belong to. Modeling and analysis of the resulting interconnected system is crucial to design efficient and effective search algorithms and to control the cost of interconnection. To this end, we develop a generalized random graph based model that is validated against simulations and it is used to investigate the performance of search algorithms for different interconnection costs and to provide some insight in the characteristics of the interconnection of a large number of P2P networks. To overcome this strong limitation, we develop a generalized random graph based model to represent the topology of one unstructured P2P network, the partition of nodes into Synapses, the probabilistic flooding based search algorithms, and the resource popularity. We validate our model against simulations and prove that its predictions are reliable and accurate. We use the model to investigate the performance and the cost of different search strategies in terms of the probability of successfully locating at least one copy of the resource and the number of queries as well as the interconnection cost. We also gain interesting insights on the dependency between interconnection cost and statistical properties of the distribution of Synapses. Finally, we show that thanks to our model we can analyze the performance of a system composed of a large number of P2P networks.

To the best of our knowledge, this is the first paper on model-based analysis of interconnection of large scale unstructured P2P networks [11] and the full version has been accepted to the conference [30].

6.3. SIEVE: a distributed, accurate, and robust technique to identify malicious nodes in data dissemination on MANET

Participants: Rossano Gaeta [Univ. Turin], Riccardo Loti [contact], Marco Grangetto [Univ Turin].

We consider the following problem: nodes in a MANET must disseminate data chunks using rateless codes but some nodes are assumed to be malicious, i.e., before transmitting a coded packet they may modify its payload. Nodes receiving corrupted coded packets are prevented from correctly decoding the original chunk. We propose SIEVE, a fully distributed technique to identify malicious nodes.

SIEVE is based on special messages called *checks* that nodes periodically transmit. A check contains the list of nodes identifiers that provided coded packets of a chunk as well as a flag to signal if the chunk has been corrupted. SIEVE operates on top of an otherwise reliable architecture and it is based on the construction of a *factor graph* obtained from the collected checks on which an incremental belief propagation algorithm is run to compute the probability of a node being malicious. Analysis is carried out by detailed simulations using ns-3. We show that SIEVE is very accurate and discuss how nodes speed impacts on its accuracy. We also show SIEVE robustness under several attack scenarios and deceiving actions. The paper has been accepted to [12] and a journal version in [26].

6.4. CCN-TV: a data-centric approach to real-time video services

Participants: Luigi Liquori, Vincenzo Ciancaglini [contact], Riccardo Loti, Giuseppe Piro [Politech Bari], Alfredo Grieco [Politech Bari].

Content Centric Networking is a promising data-centric architecture, based on in-network caching, name-driven routing, and receiver-initiated sessions, which can greatly enhance the way Internet resources are currently used, thus making the support for a broader set of users with increasing traffic demands possible. The CCN vision is, currently, attracting the attention of many researchers across the world, because it has all the potential to become ready to the market, to be gradually deployed in the Internet of today, and to facilitate a graceful transition from a host-centric networking rationale to a more effective data-centric working behavior. At the same time, several issues have to be investigated before CCN can be safely deployed at the Internet scale. They include routing, congestion control, caching operations, name-space planning, and application design. With reference to application-related facets, it is worth to notice that the demand for TV services is growing at an exponential rate over the time, thus requiring a very careful analysis of their performance in CCN architectures. To this end, in the present contribution we deploy a CCN-TV system, able to deliver real-time streaming TV services and we evaluate its performance through a simulation campaign based on real topologies. The paper has been accepted to [31] and [28] and a full version has been invited and will appear as book chapter to [33].

6.5. Towards a Trust and Reputation Framework for Social Web Platforms and @-economy

Participants: Thao Nguyen [contact], Bruno Martin [Unice], Luigi Liquori, Karl Hanks.

Trust and reputation systems (TRSs) have recently seen as a vital asset for the safety of online interaction environment. They are present in many practical applications, e.g., e-commerce and social web. A lot of more complicated systems in numerous disciplines also have been studied and proposed in academia. They work as a decision support tool for participants in the system, helping them decide whom to trust and how trustworthy the person is in fulfilling a transaction. They are also an effective mechanism to encourage honesty and cooperation among users, resulting in healthy online markets or communities. The basic idea is to let parties rate each other so that new public knowledge can be created from personal experiences. The greatest challenge in designing a TRS is making it robust against malicious attacks. In this paper, we provide readers an overview on the research topic of TRSs, propose a consistent research agenda in studying and designing a robust TRS, and present an implemented reputation computing engine alongside simulation results, which is our preliminary work to acquire the target of a trust and reputation framework for social web applications.

Information concerning the reputation of individuals has always been spread by word-of-mouth and has been used as an enabler of numerous economic and social activities. Especially now, with the development of technology and, in particular, the Internet, reputation information can be broadcast more easily and faster than ever before. Trust and Reputation Systems (TRSs) have gained the attention of many information and computer scientists since the early 2000s. TRSs have a wide range of applications and are domain specific. The multiple areas where they are applied, include social web platforms, e-commerce, peer-to-peer networks, sensor networks, ad-hoc network routing, and so on. Among these, we are most interested in social web platforms. We observe that trust and reputation is used in many online systems, such as online auction and shopping websites, including eBay, where people buy and sell a broad variety of goods and services, and Amazon, which is a world famous online retailer. Online services with TRSs provide a better safety to their users. A good TRS can also create incentives for good behavior and penalize damaging actions. Markets with the support of TRSs will be healthier, with a variety of prices and quality of service. TRSs are very important for an online community, with respect to the safety of participants, robustness of the network against malicious behavior and for fostering a healthy market.

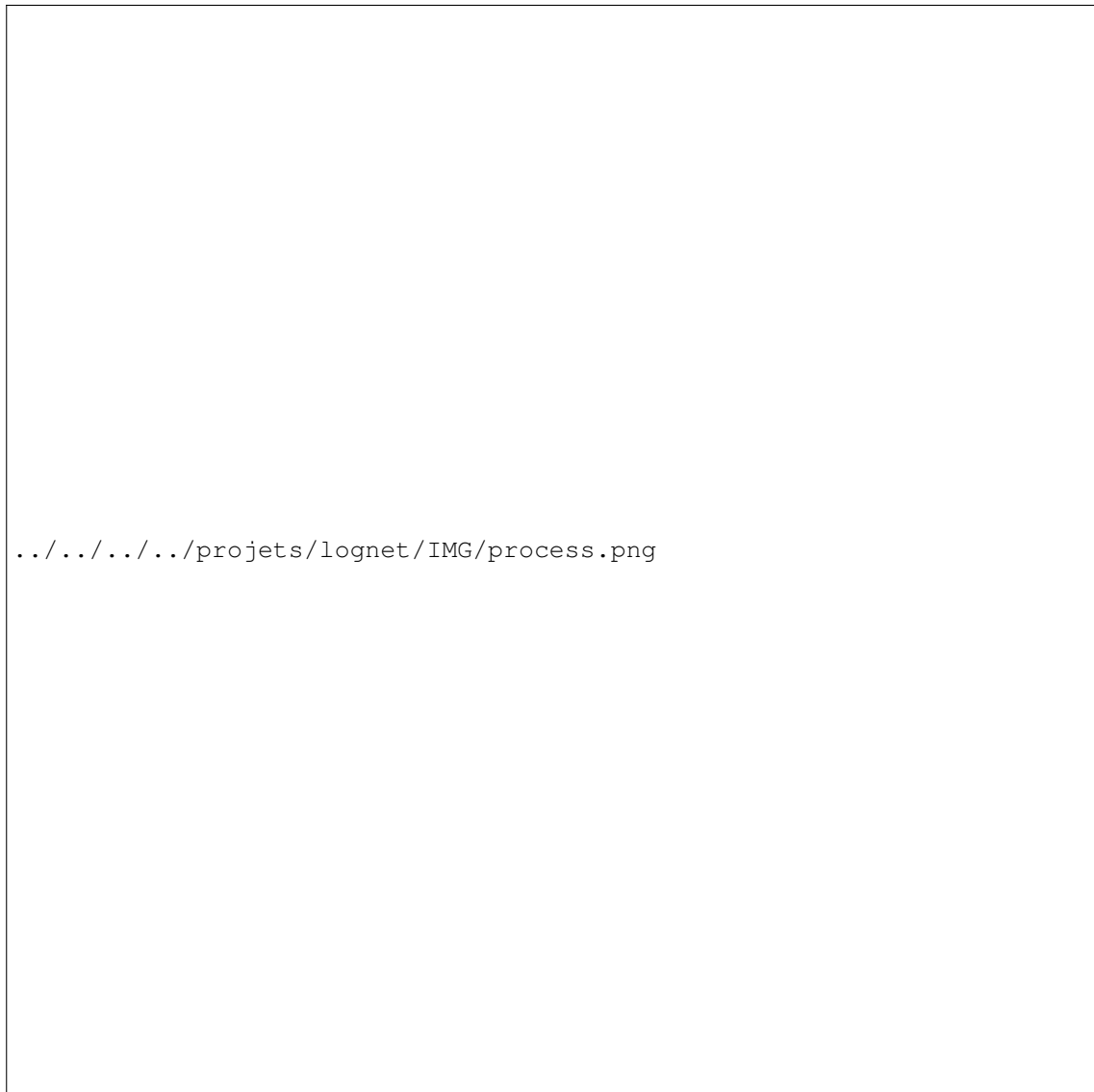


Figure 12. Process of designing a robust trust and reputation system

From a functional point of view, a TRS can be split into three components. The first component gathers feedback on participants' past behavior from the transactions that they were involved in. This component includes storing feedback from users after each transaction they take part in. The second component computes reputation scores for participants through a Reputation Computing Engine (RCE), based on the gathered information. The third component processes the reputation scores, implementing appropriate reward and punishment policies if needed, and representing reputation scores in a way which gives as much support as possible to users' decision-making. A TRS can be centralized or distributed. In centralized TRSs, there is a central authority responsible for collecting ratings and computing reputation scores for users. Most of the TRSs currently on the Internet are centralized, for example the feedback system on eBay and customer reviews on Amazon. On the other hand, a distributed TRS has no central authority. Each user has to collect ratings and compute reputation scores for other users himself. Almost all proposed TRSs in the literature are distributed.

Some of the main unwanted behaviors of users that might appear in TRSs are: *free riding* (people are usually not willing to give feedback if they are not given an incentive to do so), *untruthful rating* (users give incorrect feedback either because of malicious intent or because of unintended and uncontrolled variables), *colluding* (a group of users coordinate their behavior to inflate each other's reputation scores or bad-mouth other competitors. Colluding motives are only clear in a specific application), *whitewashing* (a user creates a new identity in the system to replace his old one when the reputation of the old one has gone bad), *milking reputation* (at first, a participant behaves correctly to get a high reputation and then turns bad to make a profit from their high reputation score). The milking reputation behavior is more harmful to social network services and e-commerce than to the others.

This research aims to build on these studies and systematize the process of designing a TRS in general as depicted in Fig. 12. First, we characterize the application system into which we want to integrate a TRS, and find and identify new elements of information which substitute for traditional signs of trust and reputation in the physical world. Second, based on the characteristics of the application, we find suitable working mechanisms and processes for each component of the TRS. This step should answer the following questions: "What kind of information do we need to collect and how?", "How should the reputation scores be computed using the collected information?", and "How should they be represented and processed to lead users to a correct decision?". To answer the first question, which corresponds to the information gathering component, we should take advantage of information technology to collect the vast amounts of necessary data. An RCE should meet these criteria: *accuracy* for long-term performance (distinguishing a newcomer with unknown quality from a low-quality participant who has stayed in the system for a long time), *weighting* towards recent behavior, *smoothness* (adding any single rating should not change the score significantly), and *robustness* against attacks. Third, we study the tentative design obtained after the second step in the presence of selfish behaviors. During the third step, we can repeatedly return to Step 2 whenever appropriate until the system reaches a desired performance. The fourth step will refine the TRS and make it more robust against malicious attacks. If a modification is made, we should return to Step 2 and check all the conditions in steps 2 and 3 before accepting the modification. The paper has been accepted to [22] and an improved software and a full paper are in preparation in 2014.

6.6. A Scalable Communication Architecture for Advanced Metering Infrastructure

Participants: Giang Ngo Hoang [contact], Luigi Liquori, Hung Nguyen Chan [VIELINA, Vietnam].

Advanced Metering Infrastructure (AMI), seen as foundation for overall grid modernization, is an integration of many technologies that provides an intelligent connection between consumers and system operators. One of the biggest challenge that AMI faces is to scalable collect and manage a huge amount of data from a large number of customers. In our paper, we address this challenge by introducing a mixed peer-to-peer (P2P) and client-server communication architecture for AMI in which metering data is aggregated and processed distributedly at multiple levels and in a tree-like manner. Through analysis we show that the architecture is featured with load scalability, resiliency with failure and partly self-organization. The

experiments performed in large scale French Grid5000 platform [G5k] shows the communication efficiency in the proposed architecture. A technical report will be submitted to an international conference [37].

6.7. An Open Logical Framework

Participants: Luigi Liquori [contact], Marina Lenisa [Univ. Udine], Furio Honsell [Univ. Udine], Petar Maksimovic, Ivan Scagnetto [Univ. Udine].

The LFP Framework is an extension of the Harper-Honsell-Plotkin’s Edinburgh Logical Framework LF with external predicates, hence the name Open Logical Framework. This is accomplished by defining lock type constructors, which are a sort of “diamond”-modality constructors, releasing their argument under the condition that a possibly external predicate is satisfied on an appropriate typed judgement. Lock types are defined using the standard pattern of constructive type theory, i.e. via introduction, elimination, and equality rules. Using LFP, one can factor out the complexity of encoding specific features of logical systems which would otherwise be awkwardly encoded in LF, e.g. side-conditions in the application of rules in Modal Logics, and sub-structural rules, as in non-commutative Linear Logic. The idea of LFP is that these conditions need only to be specified, while their verification can be delegated to an external proof engine, in the style of the Poincaré Principle or Deduction Modulo. Indeed such paradigms can be adequately formalized in LFP. We investigate and characterize the meta-theoretical properties of the calculus underpinning LFP: strong normalization, confluence, and subject reduction. This latter property holds under the assumption that the predicates are well-behaved, i.e. closed under weakening, permutation, substitution, and reduction in the arguments. Moreover, we provide a canonical presentation of LFP, based on a suitable extension of the notion of $\beta\eta$ -long normal form, allowing for smooth formulations of adequacy statements.

LFP is parametric over a potentially unlimited set of (well-behaved) predicates P , which are defined on derivable typing judgements of the form $\Gamma \vdash_{\Sigma} N : \sigma$, see Fig 13 .

The syntax of LFP predicates is not specified, with the main idea being that their truth is to be verified via a call to an external validation tool; one can view this externalization as an oracle call. Thus, LFP allows for the invocation of external “modules” which, in principle, can be executed elsewhere, and whose successful verification can be acknowledged in the system via L-reduction. Pragmatically, lock types allow for the factoring out of the complexity of derivations by delegating the {checking, verification, computation} of such predicates to an external proof engine or tool. The proof terms themselves do not contain explicit evidence for external predicates, but just record that a verification {has to be (lock), has been successfully (unlock)} carried out. In this manner, we combine the reliability of formal proof systems based on constructive type theory with the efficiency of other computer tools, in the style of the Poincaré Principle. In this paper, we develop the meta-theory of LFP. Strong normalization and confluence are proven without any additional assumptions on predicates. For subject reduction, we require the predicates to be well-behaved, i.e. closed under weakening, permutation, substitution, and $\beta\mathcal{L}$ -reduction in the arguments. LFP is decidable, if the external predicates are decidable. We also provide a canonical presentation of LFP, based on a suitable extension of the notion of $\beta\eta$ -long normal form. This allows for simple proofs of adequacy of the encodings. In particular, we encode in LFP the call-by-value λ -calculus and discuss a possible extension which supports the design-by-contract paradigm. We provide smooth encodings of side conditions in the rules of Modal Logics, both in Hilbert and Natural Deduction styles. We also encode sub-structural logics, i.e. non-commutative Linear Logic. We also illustrate how LFP can naturally support program correctness systems and Hoare-like logics. In our encodings, we utilize a library of *external predicates*. As far as expressiveness is concerned, LFP is a stepping stone towards a general theory of shallow vs deep encodings, with our encodings being shallow by definition. Clearly, by Church’s thesis, all external decidable predicates in LFP can be encoded, possibly with very deep encodings, in standard LF. It would be interesting to state in a precise categorical setting the relationship between such deep internal encodings and the encodings in LFP. LFP can also be viewed as a neat methodology for separating the logical-deductive contents from, on one hand, the verification of structural and syntactical properties, which are often needlessly cumbersome but ultimately computable, or, on the other hand, from more general means of validation. This work has been published in the ACM workshops [13] and [29] and a long version has been invited and appear in the Journal of Logic and Computation [27].



Figure 13. Some rule of the Open Logical Framework

MAESTRO Project-Team

5. New Results

5.1. Network Science

Participants: Eitan Altman, Konstantin Avrachenkov, Mahmoud El Chamie, Julien Gaillard, Philippe Nain, Giovanni Neglia, Marina Sokol.

5.1.1. Epidemic models of propagation of content

In [15], E. Altman and P. Nain, in collaboration with Y. Xu (MAESTRO member at the time of submission) and A. Shwartz (Technion, Israel), focus on the propagation of content in peer-to-peer (P2P) networks. They first study the transient behavior of some P2P networks whenever information is replicated and disseminated according to epidemic-like dynamics. They then use the insight gained from the previous analysis in order to predict how efficient could measures taken against P2P networks be. They first introduce a stochastic model which extends a classical epidemic model, and characterize the P2P swarm behavior in presence of free riding peers. They then study a second model in which a peer initiates a contact with another peer chosen randomly. In both cases the network is shown to exhibit phase transitions: a small change in the parameters causes a large change in the behavior of the network. The authors show, in particular, how phase transitions affect measures of content providers against P2P networks that distribute non-authorized music, books or articles, and what is the efficiency of counter-measures. In addition, this analytic framework can be generalized to characterize the heterogeneity of cooperative peers.

5.1.2. The design of recommendation systems (RS) for social networks

Recommendation systems take advantage of products and users information in order to propose items to targeted consumers. In [50], J. Gaillard, E. Altman, M. El Bèze and E. Ethis (both from Univ. Avignon) propose a framework to overcome the usual scalability issues of nowadays systems. The system includes a dynamic adaptation to enhance the accuracy of rating predictions by applying a new similarity measure. They perform several experiments on films data from Vodkaster, showing that systems incorporating dynamic adaptation improve significantly the quality of recommendations compared to static ones.

In [51] the same authors propose new modifications of the recommendation algorithm that allow not only to present a recommendation but also to propose a list of words which appeared frequently in recommendations of other people who watched that film and who have been identified to have similar preferences, according to their opinions on common movies.

5.1.3. Network centrality measures

A class of centrality measures called betweenness centralities reflects degree of participation of edges or nodes in communication between different parts of the network. The original shortest-path betweenness centrality is based on counting shortest paths which go through a node or an edge. One of shortcomings of this metric is that it ignores the paths that might be one or two hops longer than the shortest paths, while the edges on such paths can be important for communication processes in the network. To rectify this shortcoming a current flow betweenness centrality has been proposed. Similarly to the shortest-path betweenness, it has prohibitive complexity for large size networks. In [42] K. Avrachenkov, N. Litvak (Univ. of Twente, the Netherlands), V. Medyanikov (St. Petersburg State Univ., Russia) and M. Sokol propose and analyze two regularizations of the current flow betweenness centrality, α -current flow betweenness and truncated α -current flow betweenness, which can be computed fast and correlate well with the original current flow betweenness. In particular, the new centrality measures indicate well vulnerability of a network.

5.1.4. Average consensus protocols

Information can flow in a network through communication links connecting the nodes. Not all the links have the same importance and it is common in complex networks to distinguish “weak” links/ties and “strong” ones. Depending on the specific network, the strength of a link connecting two nodes can be quantified by its transmission capacity, the inter-meeting rate between the two nodes, the level of mutual trust of the two nodes, etc.. The topology of connections and the strength of the links are two factors that affect the speed of spread of information in the network. In [63], M. El Chamie and G. Neglia in collaboration with L. Severini (student at Univ. of Nice Sophia Antipolis, France) have shown that the topology can have stronger effect on the information spread than the strength of the links. In particular, they have considered an iterative belief propagation process as in average consensus protocols where each node in the network has a certain belief (a real number) that is updated iteratively by the weighted average of the nodes’ belief and the ones they connected to. They have shown by simulations on random graphs that a topological optimization can have a significant faster spread of beliefs than any weight selection optimization techniques. They have also given a 2-hop message averaging that performs faster convergence than standard algorithms.

The activity on “Reducing communication overhead of average consensus protocols”, described in MAESTRO’s 2012 activity report has led to the publication [49].

5.2. Wireless Networks

Participants: Eitan Altman, Philippe Nain, Giovanni Neglia, Oussama Habachi.

5.2.1. Delay Tolerant Networks

We have pursued our study of optimal control in delay tolerant network. We studied the trade-off between delivery delay and energy consumption in a delay tolerant network in which a message (or a file) has to be delivered to each of several destinations by epidemic relaying. In addition to the destinations, there are several other nodes in the network that can assist in relaying the message. The optimal control policy was obtained in the mean-field limit of large number of mobiles by C. Singh, E. Altman, A. Kumar and R. Sundaesan in [33].

Our analysis of DTNs so far was done with mobility models in which all individuals move independently of each other. In [61], S. Patil, M. Kumar and E. Altman have studied through simulations the multicast time in DTNs where the mobility of individuals follow dependent movement such as the one of flocking birds. This model is typical to cooperative movement and could be useful to describe a rescue team in an area hit by a disaster. We showed the impact of the parameters defining the mobility on the multicast time. If instead of broadcasting packets one first codes them (using network coding) then one can obtain substantial gain in the performance. This is shown in the case that all packets that are to be sent are available for coding before transmission. In [16], E. Altman studies in collaboration with F. de Pellegrini (CREATE-NET) and L. Sassatelli how to optimally decide on the amount of coded packets to create as a function of time in the case that the information to be coded is not available before transmission. This allows to optimize the system performance for the case of real-time traffic.

In [11], A. Ali, M. Panda, T. Chahed and E. Altman design and study a reliable transport protocol for DTNs consisting of both unicast and multicast flows. The improvement in reliability is brought in by a novel Global Selective ACKnowledgment (G-SACK) scheme and random linear network coding (RLC). The motivation for using network coding and G-SACKs comes from the observation that one should take the maximum advantage of the contact opportunities which occur quite infrequently in DTNs. Network coding and G-SACKs perform “mixing” of packet and acknowledgment information, respectively, at the contact opportunities and essentially solve the randomness and finite capacity limitations of DTNs. In contrast to earlier work on network coding in DTNs, we observe and explain the gains due to network coding even under an inter-session setting. Our results from extensive simulations of appropriately chosen “minimal” topologies quantify the gains due to each enhancement feature. In a related publication [67], A. Ali, L. Sassatelli, E. Altman and T. Chahed present an overview of theoretical background that is used for evaluating transport protocols in DTNs.

In [13], E. Altman formulates in collaboration with A. P. Azad, T. Başar (Univ. Illinois at Urbana Champaign) and F. De Pellegrini (CREATE-NET) a problem where both transmission and activation of mobile terminals are controlled as a linear optimal control problem. They solve the problem by making use of this linearity in order to obtain explicit expressions for the objective function as a function of the control actions trajectories (rather than as a function of both actions and state trajectories). This allows them to compute the optimal strategies explicitly.

In [26], E. Altman studies in collaboration with D. Fiems (Ghent Univ.) a class of Markov-modulated stochastic recursive equations. This class includes multi-type branching processes with immigration as well as linear stochastic equations. Conditions are established for the existence of a stationary solution and expressions for the first two moments of this solution are found. Furthermore, the transient characteristics of the stochastic recursion are investigated: the first two moments of the transient solution are obtained as well. Finally, to illustrate the approach, the results are applied to the performance evaluation of packet forwarding in delay-tolerant mobile ad-hoc networks.

In [34], G. Neglia in collaboration with X. Zhang, H. Wang (both from Fordham Univ., Bronx, USA), J. Kurose and D. Towsley (both from Univ. of Massachusetts at Amherst, USA) has also investigated the benefits of applying Random Linear Coding (RLC) to unicast application in DTNs. Under RLC, nodes store and forward random linear combinations of packets as they encounter each other. For the case of a single group of packets originating from the same source and destined for the same destination, they have proved a lower bound on the probability that the RLC scheme achieves the minimum time to deliver the group of packets. Although RLC achieves a significant reduction in group delivery delay, it fares worse in terms of average packet delivery delay and network transmissions. When replication control is employed, RLC schemes reduce the group delivery delay without increasing the number of transmissions. In general, the benefit achieved by RLC is more significant under stringent resource (bandwidth and buffer) constraints, limited signaling, highly dynamic networks, and when it is applied to packets from same flow. For more practical settings with multiple continuous flows in the network, the researchers have shown the importance of deploying RLC schemes with a carefully tuned replication control in order to achieve reduction in average delay.

In [60], the same authors investigated the problem of determining the routing that minimizes the maximum/average delivery time or the maximum/average delivery delay for a set of packets in a deterministic Delay Tolerant Network, i.e. in a network for which all the nodes' transmission opportunities are known in advance. While the general problem with multiple sources and multiple destinations is NP-hard, they have presented a polynomial-time algorithm that can efficiently compute the optimal routing in the case of a single destination or of a single packet that needs to be routed to multiple destinations.

In [59], P. Nain in collaboration with D. Towsley (Univ. of Massachusetts at Amherst, USA), A. Bar-Noy and F. Yu (both from City Univ. of New York, USA), P. Basu (Raytheon BBN Technologies, USA), and M. P. Johnson (Univ. of California, Los Angeles, USA) consider the problem of estimating the end-to-end latency of intermittently connected paths in disruption/delay tolerant networks. While computing the time to traverse such a path may be straightforward in fixed, static networks, doing so becomes much more challenging in dynamic networks, in which the state of an edge in one timeslot (i.e., its presence or absence) is random, and may depend on its state in the previous timeslot. The authors compute the expected traversal time (ETT) for a dynamic path in a number of special cases of stochastic edge dynamics models, and for three different edge failure models, culminating in a surprisingly nontrivial yet realistic "hybrid network" setting in which the initial configuration of edge states for the entire path is known. The ETT for this "initial configuration" setting can be computed in quadratic time (as a function of path length), by an algorithm based on probability generating functions. Several linear-time upper and lower bounds on the ETT are provided and evaluated using numerical simulations.

5.2.2. Interference coordination in wireless networks

In [47], R. Combes, E. Altman and Z. Altman (Orange Labs, Issy les Moulineaux) model a LTE wireless network with Inter-Cell Interference Coordination (ICIC) at the flow level where users arrive and depart dynamically, in order to optimize quality of service indicators perceivable by users such as file transfer time

for elastic traffic. They propose an algorithm to tune the parameters of ICIC schemes automatically based on measurements. The convergence of the algorithm to a local optimum is proven, and a heuristic to improve its convergence speed is given. Numerical experiments show that the distance between local optima and the global optimum is very small, and that the algorithm is fast enough to track changes in traffic on the time scale of hours. The proposed algorithm can be implemented in a distributed way with very small signaling load.

In [46], the same authors introduce self-organizing mechanisms as control loops, and study the conditions for stability when running control loops in parallel. Based on control theory, they propose a distributed coordination mechanism to stabilize the system. In certain cases, coordination can be achieved without any exchange of information between control loops. The mechanism remains valid in the presence of noise via stochastic approximation. Instability and coordination in the context of wireless networks are illustrated with two examples. The paper is essentially concerned with linear systems, and the applicability of our results for non-linear systems is discussed.

5.2.3. Streaming over wireless

The Quality of Experience (QoE) of streaming service is often degraded by playback interruptions. To mitigate these, the media player prefetches streaming contents before starting playback, at a cost of delay. In [66], Y. Xu, S. E. Elayoubi, E. Altman and R. El-Azouzi study the QoE of streaming from the perspective of flow dynamics. First, a framework is developed for QoE when streaming users join the network randomly and leave after downloading completion. They compute the distribution of prefetching delay using partial differential equations, and the probability generating function of playout buffer starvation using ordinary differential equations. Second, they extend the framework to characterize the throughput variation caused by opportunistic scheduling at the base station in the presence of fast fading. This study reveals that the flow dynamics is the fundamental reason of playback starvation. The QoE of streaming service is dominated by the average throughput of opportunistic scheduling, while the variance of throughput has very limited impact on starvation behavior.

5.2.4. Dynamic coverage of mobile sensor networks

B. Liu (Univ. of Massachusetts at Lowell, USA), O. Dousse (Nokia Research Center, Switzerland), P. Nain, and D. Towsley (Univ. of Massachusetts at Amherst, USA) study in [30] the dynamic aspects of the coverage of a mobile sensor network resulting from continuous movement of sensors. As sensors move around, initially uncovered locations may be covered at a later time, and intruders that might never be detected in a stationary sensor network can now be detected by moving sensors. However, this improvement in coverage is achieved at the cost that a location is covered only part of the time, alternating between covered and not covered. The authors characterize area coverage at specific time instants and during time intervals, as well as the time durations that a location is covered and uncovered. They further consider the time it takes to detect a randomly located intruder and prove that the detection time is exponentially distributed. For mobile intruders, a game theoretic approach allows to derive optimal mobility strategies for both sensors and intruders. The optimal sensor strategy is to choose the direction uniformly at random between 0 and 2π . The optimal intruder strategy is to remain stationary. This solution represents a mixed strategy which is a Nash equilibrium of the zero-sum game between mobile sensors and intruders.

5.2.5. Wireless network security

The activity on “Fast and secure rendezvous protocols for mitigating control channel DoS attacks” described in MAESTRO’s 2012 activity report has led to the publication [35].

5.3. Network Engineering Games

Participants: Eitan Altman, Konstantin Avrachenkov, Ilaria Brunetti, Julien Gaillard, Majed Haddad, Manjesh Kumar Hanawal, Alexandre Reiffers.

5.3.1. Association problem

In [32], A. Silva, in collaboration with H. Tembine, E. Altman and M. Debbah, study a non-cooperative association game where mobiles associate to Base Stations. The authors solve the problem using the theory of optimal transportation after incorporating in it the effect of network congestion. They are able to find a closed form expression for its solution. The authors also solve a global optimization problem for minimizing the total power needed by the mobile terminals over the whole network.

5.3.2. Cognitive radio

In [52] O. Habachi considers a non-cooperative Opportunistic Spectrum Access (OSA) where Secondary Users (SUs) access opportunistically the spectrum licensed for Primary Users (PUs) in TV white spaces (TVWS). As sensing licensed channels is time and energy consuming, the author considers a hierarchical Cognitive Radio (CR) architecture, where CR base stations sense a subset of the spectrum in order to locate some free frequencies. Thereafter, a SU that needs to communicate through TVWS sends a request to a CR base station for a free channel. The author models the problem using a Partially Observable Stochastic Game (POSG), and he takes into consideration the energy consumption of CR base stations and the Quality of Service of SUs. Since solving POSG optimally may require a significant amount of time and computational complexity, the author then models the OSA problem using a game theoretical approach, and proposes a symmetric Nash equilibrium solution concept. Finally, the simulations that validate the theoretical findings are provided.

In [24], J. Elias (Univ. Paris Descartes), F. Martignon (Univ. Paris Sud), L. Chen and E. Altman address the joint pricing and network selection problem in cognitive radio networks. The problem is formulated as a Stackelberg game where first the Primary and Secondary operators set the network subscription price to maximize their revenue. Then, users perform the network selection process, deciding whether to pay more for a guaranteed service, or use a cheaper, best-effort secondary network, where congestion and low throughput may be experienced. They use the Nash equilibrium concept to characterize the equilibria for the price setting game. On the other hand, a Wardrop equilibrium is used in the network selection game.

5.3.3. Cooperative games in wireless networks

We have pursued this year our new activity on cooperative games in wireless communications. We have pursued our work on coalition games and started working on the area of matching games. In [56], E. Altman, C. Hasan and J.-M. Gorce (both from Inria project-team SOCRATE) have addressed the problem of association of mobiles to base stations which can be viewed as a coalition game. They formulated the game using a stochastic geometric approach (one Poisson point process representing the base stations and another one representing the mobiles) and studied the impact of switching off base stations (for energy efficient operation).

An important class of games within cooperative games is the matching games. They have been used in stable marriage games (in which a bi-partite graph called matching is to be proposed between a group of men and women based on mutual ranking between this group). A second well-known application of matching games is the college admission problem in which students are assigned to colleges based on their preferences as well as on the preferences of the colleges. We introduced and solved two matching games in wireless communication using the theory of matching games. In [55] the same authors study a game similar to the above ones to match pairs of mobiles where one mobile serves as a relay for the other in the absence of a good direct channel to the base station. The utilities studied here are the outage probabilities. In [65], R. Vaca-Ramirez, E. Altman, J. S. Thompson and V. Ramos-Ramos propose a distributed algorithm for energy efficient virtual Multiple-input/Multiple-output coalition formation. They model cooperation as a game derived from the concept of stable marriage with incomplete lists. Single antenna devices such as mobile and relay stations cooperate in order to improve the user's and system's energy efficiency. In both problems above, the performance of the equilibrium is shown to be close to the social optimum and yet the complexity for achieving the equilibrium is only polynomial (whereas that of computing a global optimal matching is NP hard).

In [40] K. Avrachenkov, L. Cottatellucci (EURECOM) and L. Maggi (CREATE-NET, Italy) study multiple access channels whose channel coefficients follow a quasi-static Markov process on a finite set of states. The authors address the issue of allocating transmission rates to users in each time interval, such that optimality and

fairness of an allocation are preserved throughout a communication, and moreover all the users are consistently satisfied with it. First, it is shown how to allocate the rates in a global optimal fashion. The authors provide a sufficient condition for the optimal rates to fulfill some fairness criteria in a time-consistent way. Then the authors utilize the game-theoretical concepts of time consistent Core and Cooperation Maintenance. It is demonstrated that in the model the sets of rates fulfilling these properties coincide and they also coincide with the set of global optimal rate allocations. The relevance of the presented dynamic rate allocation to LTE systems is also shown.

5.3.4. Bayesian games in networking

K. Veeraruna, E. Altman, R. El-Azouzi and S. Rajesh have studied in [29] a power control problem in which a base station allocates power according to the channel state as reported by the mobiles. The paper addresses the question of how to allocate the power, given that the channel reported by some non-cooperative mobile may be unreliable. They obtain the equilibrium allocation after formulating the problem as a Bayesian game.

In [38], E. Altman and T. Jiménez consider both a cooperative as well as non-cooperative admission into an M/M/1 queue. The only information available is a signal that says whether the queue size is smaller than some value L or not. They first compute the globally optimal and the Nash equilibrium stationary policy as a function of L . They compare the performance to that of full information and of no information on the queue size. They identify the value of L that optimizes the equilibrium performance.

In [58], K. Ibrahimi, E. Altman and M. Haddad introduce a signaling game approach to power control. They consider two players named player I and player II. They assume that player I only knows his channel state without any information about the channel state of player II and vice-versa. Player I moves first and sends a signal to player II which can be accurate or distorted. Player II chooses his power control strategy based on this information and his belief about the nature of the informed player's information. In order to analyze such a model, the proposed scheme game is transformed into an equivalent 4x4 matrix game. The authors establish the existence of Nash equilibria and then derive it numerically and study its properties.

In [53], M. Haddad and E. Altman, in collaboration with P. Wiecek and H. Sidi, present a Bayesian game theoretic framework for determining the decision to which cell a given mobile user should associate in LTE two-tier Heterogeneous Networks. Users are assumed to compete to maximize their throughput by picking the best locally serving cell with respect to their own measurement, their demand and a partial statistical channel state information of other users. In particular, the authors investigate the properties of a hierarchical game, in which the macro-cell BS is a player on its own. They derive analytically the utilities related to the channel quality perceived by users to obtain the equilibria. They show in the Stackelberg formulation, how the operator, by dynamically choosing the offset about the state of the channel, can optimize its global utility while end-users maximize their individual utilities.

5.3.5. Network neutrality and collusion

Representatives of several Internet access providers have expressed their wish to see a substantial change in the pricing policies of the Internet. In particular, they would like to see content providers pay for use of the network, given the large amount of resources they use. This would be in clear violation of the "network neutrality" principle that had characterized the development of the wireline Internet. We proposed and studied possible ways of implementing such payments and of regulating their amount. M. K. Hanawal and E. Altman have pursued in [54] working on network neutrality studying various ways of collusion between an ISP and a content provider and in particular, another form of non-neutrality in which a content provider signals to an ISP information on the popularity of its content and hides this information from other ISPs. They define and compute the price of collusion and study the impact of such signalling on the ISP that is in collusion as well as on the other ones.

In the situation just described, the demand is modelled to be elastic. In contrast, in [62], A. Reiffers and E. Altman study in collaboration with Y. Hayel pricing issues in non-neutral network with non-elastic traffic. A Stackelberg equilibrium is derived and the price of collusion is computed.

Our research on network neutrality started already on 2010 with a research report [83] that has now been published in [14]. We already reported on this publication in 2011 when it became available electronically.

5.3.6. Competition over popularity in social networks

In [39] E. Altman, P. Kumar, S. Venkatramanan and A. Kumar consider a situation where several content producers send their content to some subscriber of a social network. These posts appear on the subscriber's timeline which is assumed to have finite capacity. Whenever a new post arrives to the timeline, an older post leaves it. Therefore to be visible, a source has to keep sending contents from time to time. Each source is modelled as a player in a non-cooperative game in which one trades between the utility for being visible on the timeline and the cost (or effort) for keeping sending content. This game is solved in a Markovian setting the performance measures of interest are computed.

In [37], E. Altman in cooperation with F. De Pellegrini (CREATE-NET), D. Miorandi, T. Jiménez and R. El-Azouzi study situations in which subscribers of a social network take the decision whether to access or not some content, based on the number of views that the content has. Their analysis aims at understanding the way in which information about the quality of a given content can be deduced from view counts when only part of the viewers that access the content are informed about its quality. In this paper they present a game formulation for the behavior of individuals using a mean-field model: the number of individuals is approximated by a continuum of atomless players and for which the Wardrop equilibrium is the solution concept. They derive conditions on the problem's parameters that result in the emergence of threshold equilibria policies. But they also identify some parameters in which other structures are obtained for the equilibrium behavior of individuals.

5.3.7. Evolutionary games

Evolutionary game theory is a relatively young mathematical theory that aims at formalizing in mathematical terms evolution models in biology. In recent years this paradigm has penetrated more and more into other areas such as the linguistics, economics and engineering. The current theory of evolutionary game makes an implicit assumption that the evolution is driven by selfishness of individuals who interact with each other. In mathematical terms this can be stated as "an individual equals a player in a non-cooperative game model". This assumption turns out to be quite restrictive in modeling evolution in biology. It is now more and more accepted among biologist that the evolution is driven by the selfish interests of large groups of individuals; a group may correspond for example to a whole beehive or to an ants' nest. In [43] and [71], I. Brunetti and E. Altman propose an alternative paradigm for modeling evolution where a player does not necessarily represent an interacting individual but a whole class of such individuals. In [71] in particular, they use Markov Decision Evolutionary Games (MDEG) to allow a parent and a child represent the same individual at different states. This is yet another enhancement in what we understand as a player. An important contribution is in the study of the Hawk and Dove game in these new frameworks.

In [27], M. Haddad, J. Gaillard, E. Altman and D. Fiems (Ghent Univ.) study an evolutionary game in the MDEG framework of power control. Aging is taken into account by assuming that as the battery of the mobile becomes empty, high power is not available anymore. The goal of a mobile is to use power that maximizes the amount of traffic it can transmit during its lifetime. We restrict in this work to policies that are state independent and compute the equilibrium.

5.4. Green Networking and Smart Grids

Participants: Sara Alouf, Eitan Altman, Nicaise Choungmo Fofack, Delia Ciullo, Alain Jean-Marie, Giovanni Neglia.

5.4.1. Stochastic geometry methods for wireless design issues

In [64] the issue of energy efficiency in Orthogonal Frequency-Division Multiple Access (OFDMA) wireless networks is discussed by D. Tsilimantou, J.-M. Gorce (Inria project-team SOCRATE) and E. Altman. Their interest is focused on the promising concept of base station (BS) sleep mode, introduced recently as a key

feature in order to dramatically reduce network energy consumption. The proposed technical approach fully exploits the properties of stochastic geometry, where the number of active cells is reduced in a way that the outage probability, or equivalently the signal to interference plus noise (SINR) distribution, remains the same. The optimal energy efficiency gains are then specified with the help of a simplified but yet realistic BS power consumption model. Furthermore, the authors extend their initial work by studying a non-singular path loss model in order to verify the validity of the analysis and finally, the impact on the achieved user capacity is investigated. In this context, the significant contribution of this paper is the evaluation of the theoretically optimal energy savings of sleep mode, with respect to the decisive role that the BS power profile plays.

5.4.2. Analysis of base stations with autonomous energy supply

S. Alouf, A. Jean-Marie and D. Ciullo have started the modeling of wireless communication base stations with autonomous energy supply (solar, wind). One challenge is to account for the random and non-stationary input of energy. A second challenge is to find the correct time and space granularity of the model, so as to ensure both the practical relevance of the model and numerical tractability. The activity will be backed up by a measurement campaign on the Com4Innov platform (<http://www.com4innov.com/>), that will provide information on energy consumption of different traffic patterns.

5.4.3. Demand-response system

Energy demand aggregators are new actors in the energy scenario: they gather a group of energy consumers and implement a demand-response paradigm. When the energy provider needs to reduce the current energy demand on the grid, it can pay the energy demand aggregator to reduce the load by turning off some of its consumers loads or postponing their activation. Currently this operation involves only greedy energy consumers like industrial plants. In [48], [78] A. Jean-Marie and G. Neglia in collaboration with G. Di Bella, L. Giarré, M. Ippolito and I. Tinnirello (all from Univ. of Palermo, Italy) have studied the potential of aggregating a large number of small energy consumers like home users as it may happen in smart grids. In particular they have addressed the feasibility of such approach by considering which scale the aggregator should reach in order to be able to control a significant power load. The challenge of the study derives from residential users' demand being much less predictable than that of industrial plants. For this reason they have resorted to queuing theory to study analytically the problem and quantify the trade-off between load control and tolerable service delays.

5.5. Content-Oriented Systems

Participants: Sara Alouf, Konstantin Avrachenkov, Nicaise Choungmo Fofack, Delia Ciullo, Alain Jean-Marie, Philippe Nain, Giovanni Neglia, Marina Sokol.

5.5.1. Performance evaluation of hierarchical TTL-based cache networks

N. Choungmo Fofack, P. Nain and G. Neglia, together with D. Towsley (Univ. of Massachusetts at Amherst, USA) have revisited and extended the work that has appeared in [82]. They consider caches that implement an expiration-based eviction policy to manage contents in their memory. These caches are called Time-To-Live (TTL)-based caches. These TTL-based caches can be used to model caches running classical replacement policies such as Least Recently Used (LRU) and Random Replacement (RND). The main characteristic of the latter TTL-based cache models is that they (re)initialize the TTL of a content at both cache hit and cache miss. In a paper that is currently under review, the case of a network of caches where requests for each content are routed as a polytree is analyzed and a framework to evaluate the performance of such general TTL-based cache networks is proposed.

5.5.2. Modeling modern DNS caches

Motivated by the recent behavior of Domain Name System (DNS) caches that do not respect the timeout marked (by Authoritative DNS servers) on resource records, N. Choungmo Fofack and S. Alouf propose in [44] a theoretical model based on renewal arguments to describe this modern behavior. The proposed model for a cache taken in isolation is validated with real traces collected by Inria's IT service at Sophia-Antipolis at one of the Inria's DNS caches. The model of a network of caches is validated by event-driven simulations. This

study suggests that, when inter-request times have a concave cumulative distribution function, client caches (those caches that are fed directly by users requests) should keep each resource record for a constant duration (that may depend on its popularity). However, core caches should draw their timeout values for each record from a distribution which has as high coefficient of variation as possible.

5.5.3. *An approximate analysis of general and heterogeneous cache networks*

Jointly with M. Dehghan, D. L. Goeckel and D. Towsley (Univ. of Massachusetts at Amherst, USA), N. Choungmo Fofack proposes a simple, accurate, and computationally efficient framework to assess performance of network of caches with arbitrary topology, requests described by renewal processes, and caches running Least Recently Used (LRU), First-In First-Out (FIFO), or Random Replacement (RND) policies. Their framework is based on the characteristic time approximation of LRU, RND and FIFO caches that helps to model the latter as TTL-based caches. Classical results of the theory of (renewal) point processes (e.g. approximation of general point processes by renewal processes, thinning a renewal point process, aggregating/merging independent renewal processes) are used as well as theoretical results established in [82] and [44] on TTL-based caches (e.g. calculation of metrics of interest such hit and occupancy probabilities, characterization of miss streams).

5.5.4. *Data placement*

Jointly with J.-C. Bermond (Inria project-team COATI), D. Mazauric (Univ. Aix-Marseille) and J. Yu (UFV Vancouver), A. Jean-Marie has pursued the study of combinatorial designs that solve the problem of replicating optimally data over unreliable servers, with the objective of minimizing the variance of the availability of documents. In a forthcoming revision of [81], they use results from Design Theory, particularly the existence of “large triple systems” to solve multiple instances of the problem.

5.5.5. *Semi-supervised learning with application to P2P systems*

Semi-supervised learning methods constitute a category of machine learning methods which use labelled points together with unlabelled data to tune the classifier. The main idea of the semi-supervised methods is based on an assumption that the classification function should change smoothly over a similarity graph, which represents relations among data points. This idea can be expressed using kernels on graphs such as graph Laplacian. Different semi-supervised learning methods have different kernels which reflect how the underlying similarity graph influences the classification results. In [41] K. Avrachenkov, P. Gonçalves (Inria project-team DANTE) and M. Sokol analyze a general family of semi-supervised methods, provide insights about the differences among the methods and give recommendations for the choice of the kernel parameters and labelled points. In particular, it appears that it is preferable to choose a kernel based on the properties of the labelled points. They illustrate our general theoretical conclusions with an analytically tractable characteristic example, clustered preferential attachment model and classification of content in P2P networks.

5.6. *Advances in Methodological Tools*

Participants: Konstantin Avrachenkov, Alain Jean-Marie, Philippe Nain.

5.6.1. *Perturbation analysis*

In [21] K. Avrachenkov and J.-B. Lasserre (LAAS-CNRS) investigate the analytic perturbation of generalized inverses. Firstly the authors analyze the analytic perturbation of the Drazin generalized inverse (also known as reduced resolvent in operator theory). The approach is based on spectral theory of linear operators as well as on a new notion of group reduced resolvent. It allows one to treat regular and singular perturbations in a unified framework. The authors provide an algorithm for computing the coefficients of the Laurent series of the perturbed Drazin generalized inverse. In particular, the regular part coefficients can be efficiently calculated by recursive formulae. Finally, the authors apply the obtained results to the perturbation analysis of the Moore-Penrose generalized inverse in the real domain.

5.6.2. Markov processes

In [20] K. Avrachenkov, L. Cottatellucci (EURECOM), L. Maggi (CREATE-NET, Italy) and Y.-H. Mao (Beijing Normal Univ., China) consider both discrete-time irreducible Markov chains with circulant transition probability matrix P and continuous-time irreducible Markov processes with circulant transition rate matrix Q . In both cases they provide an expression of all the moments of the entropy mixing time. In the discrete case, they prove that all the moments of the mixing time associated with the transition probability matrix $\alpha P + (1 - \alpha)P^*$ are maximum in the interval $0 \leq \alpha \leq 1$ when $\alpha = 1/2$, where P^* is the transition probability matrix of the time-reversed chain. Similarly, in the continuous case, they show that all the moments of the mixing time associated with the transition rate matrix $\alpha Q + (1 - \alpha)Q^*$ are also maximum in the interval $0 \leq \alpha \leq 1$ when $\alpha = 1/2$, where Q^* is the time-reversed transition rate matrix.

In [23] K. Avrachenkov, in collaboration with A. Piunovskiy and Z. Yi (both from Univ. of Liverpool, UK), study a general homogeneous continuous-time Markov process with restarts. The process is forced to restart from a given distribution at time moments generated by an independent Poisson process. The motivation to study such processes comes from modeling human and animal mobility patterns, restart processes in communication protocols, and from application of restarting random walks in information retrieval. The authors provide a connection between the transition probability functions of the original Markov process and the modified process with restarts. Closed-form expressions for the invariant probability measure of the modified process are derived. When the process evolves on the Euclidean space there is also a closed-form expression for the moments of the modified process. The authors show that the modified process is always positive Harris recurrent and exponentially ergodic with the index equal to (or bigger than) the rate of restarts. Finally, the general results are illustrated by the standard and geometric Brownian motions.

5.6.3. Queueing theory

In [22] K. Avrachenkov, P. Nain and U. Yechiali (Tel Aviv Univ., Israel) consider two independent Poisson streams of jobs flowing into a single-server service system having a limited common buffer that can hold at most one job. If a type- i job ($i = 1, 2$) finds the server busy, it is blocked and routed to a separate type- i retrial (orbit) queue that attempts to re-dispatch its jobs at its specific Poisson rate. This creates a system with three dependent queues. Such a queueing system serves as a model for two competing job streams in a carrier sensing multiple access system. We study the queueing system using multi-dimensional probability generating functions, and derive its necessary and sufficient stability conditions while solving a Riemann-Hilbert boundary value problem. Various performance measures are calculated and numerical results are presented. In particular, numerical results demonstrate that the proposed multiple access system with two types of jobs and constant retrial rates provides incentives for the users to respect their contracts.

5.6.4. Control theory

In conjunction with E. Della Vecchia and S. Di Marco (both from National Univ. Rosario, Argentina), A. Jean-Marie has pursued the studies on the Rolling Horizon procedure and other approximations in stochastic control problems. Inspired by the work of A. Ruszczyński, they have considered Markov Decision problems where the metric to be optimized is a risk measure, a metric which generalizes the mathematical expectation and takes risk aversion of agents into account. For infinite-horizon, risk-averse discounted Markov Decision Processes, they have proved approximation bounds which imply the convergence of approximate rolling horizon procedures when the horizon length tends to infinity. They have also analyzed the effects of uncertainties on the transition probabilities, the cost functions and the discount factors [77].

In [17] K. Avrachenkov, U. Ayesta (LAAS-CNRS), J. Doncel (LAAS-CNRS) and P. Jacko (BCAM, Spain) address the problem of fast and fair transmission of flows in a router, which is a fundamental issue in networks like the Internet. They focus on the relaxed version of the problem obtained by relaxing the fixed buffer capacity constraint that must be satisfied at all time epoch. The relaxation allows one to reduce the multi-flow problem into a family of single-flow problems, for which one can analyze both theoretically and numerically the existence of optimal control policies of special structure. In particular, it is shown that the control can be represented by so-called index policies, but not always by threshold policies. The simulation and numerical results show that the index policy achieves a wide range of desirable properties with respect to fairness between

different TCP versions, across users with different round-trip-time and minimum buffer required to achieve full utility of the queue.

5.6.5. Game theory

In [18] K. Avrachenkov, L. Cottatellucci (EURECOM) and L. Maggi (CREATE-NET, Italy) consider simple Markovian games, in which several states succeed each other over time, following an exogenous discrete-time Markov chain. In each state, a different simple static game is played by the same set of players. The authors investigate the approximation of the Shapley-Shubik power index in simple Markovian games (SSM). The authors prove that an exponential number of queries on coalition values is necessary for any deterministic algorithm even to approximate SSM with polynomial accuracy. Motivated by this, the authors propose and study three randomized approaches to compute a confidence interval for SSM. They rest upon two different assumptions, static and dynamic, about the process through which the estimator agent learns the coalition values. Such approaches can also be utilized to compute confidence intervals for the Shapley value in any Markovian game. The proposed methods require a number of queries, which is polynomial in the number of players in order to achieve a polynomial accuracy.

In [19] K. Avrachenkov, L. Cottatellucci (EURECOM) and L. Maggi (CREATE-NET, Italy) study multi-agent Markov decision processes (MDPs) in which cooperation among players is allowed. They find a cooperative payoff distribution procedure (MDP-CPDP) that distributes in the course of the game the payoff that players would earn in the long run game. They show under which conditions such a MDP-CPDP fulfills a time consistency property, contents greedy players, and strengthen the coalition cohesiveness throughout the game. Finally, the authors refine the concept of Core for Cooperative MDPs.

OASIS Project-Team

6. New Results

6.1. Programming and Composition Models for Large-Scale Distributed Computing

6.1.1. Multi-active Objects

Participants: Ludovic Henrio, Fabrice Huet, Justine Rochas.

The active object programming model is particularly adapted to easily program distributed objects: it separates objects into several *activities*, each manipulated by a single thread, preventing data races. However, this programming model has its limitations in terms of expressiveness – risk of deadlocks – and of efficiency on multicore machines. We proposed to extend active objects with *local multi-threading*. We rely on declarative *annotations* for expressing potential concurrency between requests, allowing easy and high-level expression of concurrency. This year we realized the following:

- publication of the multiactive object programming model in COORDINATION 2013 [19]
- extension of the annotations to support the specification of:
 - thread management. This aims at specifying (i) thread reservation and (ii) thread limitation in order to control more finely the allocation of threads in a multiactive object.
 - priority of requests. The programmer can now specify a priority graph to have an influence on the order of execution of requests in a multiactive object

This extension was initially explored in a master thesis [34] and led to a publication in SAC 2014 [21].

- extensive use of multiactive objects in our CAN P2P network and implementation of usecases.

We plan to continue to improve the model, especially about compile-time checking of annotations and about fault tolerance of multiactive objects.

6.1.2. Algorithmic skeletons

Participant: Ludovic Henrio.

In the context of the SCADA associated team, we worked on the algorithmic skeleton programming model. The structured parallelism approach (skeletons) takes advantage of common patterns used in parallel and distributed applications. The skeleton paradigm separates concerns: the distribution aspect can be considered separately from the functional aspect of an application. In the previous year we designed the possibility for a skeleton to output events, which increases the control and monitoring capabilities. This year we achieved the following objectives:

- Encapsulation of the skandium skeleton runtime in a component in order to allow distributed execution of skeletons: local parallelism is handled by skandium while distributed execution is handled by the GCM component library.
- We applied the event framework for skeletons to design a framework allowing the skeleton execution to adapt autonomically in order to achieve a required quality of service. We have first promising results on this aspect and a publication has just been accepted to PMAM 2014.

6.1.3. Behavioural models for Distributed Components

Participants: Eric Madelaine, Nuno Gaspar, Oleksandra Kulankhina, Ludovic Henrio.

In the past [3], we defined the behavioural semantics of active objects and components. This year we extended this work to address group communications. On the practical side, this work contributes to the Vercors platform; the overall picture being to provide tools to the programmer for defining his application, including its behavioural specification. Then some generic properties like absence of deadlocks, but also application specific properties, can be validated on the composed model using an existing model-checker. We mainly use the CADP model-checker, that also supports distributed generation of state-space. This year our main achievements are the following:

- We improved the specification of the behavioural model generation for component systems that we specified last year [36]. A journal version is under submission.
- We extended the formal model of the GCM architecture and included the specification of the non-functional aspects.
- We worked on the design of a bisimulation equivalence relation adapted to pNets; such an equivalence relation would justify some of the verifications and simplifications we do in our verification platform. Bisimulation theory gives tools to prove the equivalent behaviour of two processes, but adapting it to the structural nature and to the parameterized definitions of pNets is a challenging task. We have obtained promising preliminary results on this aspect: we have a good library of examples illustrating the expressiveness of pNets and use it to study bisimulation techniques.
- We additionally have put considerable efforts on the improvement of the Vercors platform (see Section 5.2). We have totally updated the Vercors Components Editor. We have integrated the UML state machines editor from Obeo UML Designer (<http://marketplace.obeonetwork.com/module/uml>) into Vercors platform. The integrated editor provides the tools for the specification of the components behavior.
- We have started implementing the behavioural semantics of [36] in the Vercors platform. This task consists in generating the behavior of GCM components in the form of pNets from the GCM architecture defined using VCE. This is an important task, involving intricate engineering issues, but also interesting research on methods for reducing the size of the generated models.

This work was done in collaboration with Rabéa Ameer-Boulifa from Télécom-Paristech and Min Zhang from ECNU Shanghai.

In parallel with core developments of the behavioural specification environment, we further collaborated with our industrial partners and enhanced our work around the use of proof assistants for our specification and verification purposes. In particular, this year:

- We made significant improvements on Mefresa, our Mechanized Framework for the Reasoning on Software Architectures. These were published in [17]. Moreover, we obtained preliminary results regarding its integration with GCM/ProActive, our java middleware for parallel and distributed programming.
- We specified, verified and implemented the HyperManager, a GCM distributed application for the management and monitoring of E-Connectware — a solution for the management of distributed RFID infrastructures. This work was published as an industrial case study in [18].

6.1.4. Autonomic Monitoring and Management of Components

Participants: Françoise Baude, Bastien Sauvan.

We have completed the design of a framework for autonomic monitoring and management of component-based applications. We have provided an implementation using GCM/ProActive taking advantage of the possibility of adding components in the membrane. The framework for autonomic computing allows the designer to describe in a separate way each phase of the MAPE autonomic control loop (Monitoring, Analysis, Planning, and Execution), and to plug them or unplug them dynamically.

- This year, we worked on a journal paper presenting our implementation of GCM component model using active objects, and its use to provide autonomic components. The paper is under revision for SPE journal.

6.1.5. Optimization of data transfer in SOA and EDA models

Participants: Amjad Alshabani, Iyad Alshabani, Françoise Baude, Laurent Pellegrino, Bastien Sauvan, Quirino Zagareze.

Traditional client-server interactions rely upon method invocations with copy of the parameters. This can be useless in particular if the receiver does not effectively uses them. On the contrary, copying and transferring parameters lazily, and allowing the receiver to proceed without only some of them is a meaningful idea that we proved to be effective for active objects in the past [38]. This idea wasn't so far realized in the context of the web services technology, the most popular one used today for client-server SOAP-based interactions.

- We contributed to the offloading of objects representing parameters of the web service Java Apache CXF API [46]. It is innovative notably in the way the offloading of parameters for on-demand access can be delegated from services to services, which resembles the concept of first-class futures from ASP.
- Relying upon such an effective approach, we have applied a similar idea of “lazy copying and transfer” to the data parts of events in the context of event-driven architecture applications [26]. The middleware dynamically off-loads data (generally of huge size) attached to an event, according to some user-level policy expressed as annotation in the Java code at the subscriber side. The event itself, without its attachments, gets forwarded into the publish/subscribe brokering system (in our case, the EventCloud middleware, see Section 5.5) and its attachments are transferred to the subscriber on-demand. Compared to some existing propositions geared towards a data centric publish-subscribe pattern (e.g. the DDS OMG standard), ours is more user-friendly as it does not require the user code to explicitly program when to get the data attached to notified events. Also it features very low performance overhead, as additional experiments conducted show it: they are reported in an extended version of the SAC 2013 paper that is under minor revision for a special issue of the Science of Computer Programming journal.

Overall, this work opens the way towards a strong convergence between service oriented and event-driven technologies.

6.1.6. Multi-layer component architectures

Participant: Olivier Dalle.

Since a few years, we have been investigating the decomposition of a simulation application into multiple layers corresponding to the various concerns commonly found in a simulation: in addition to the various modeling domains that may be found in a single simulation application (e.g. telecommunications networks, road-networks, power-grids, and so on), a typical simulation includes various orthogonal concerns such as system modelling, simulation scenario, instrumentation and observation, distribution, and so on. This large number of concerns has put in light some limits of the traditional hierarchical component-based architectures and their associated ADL, as found in the FCM and GCM. In order to cope with these limitations, we started a new component architecture model called Binding Layers centered on the binding rather than the component, with no hierarchy but advanced layering capabilities, and offering advanced support for dynamic structures. This project is composed of four levels of specification: the two first levels are ready for public release, but some work is still needed for the development of the validation prototypes.

6.2. Middleware for Grid and Cloud computing

6.2.1. Distributed algorithms for CAN-like P2P networks

Participants: Ludovic Henrio, Fabrice Huet, Justine Rochas.

The nature of some large-scale applications, such as content delivery systems or publish/subscribe systems, built on top of Structured Overlay Networks (SONs), demands application-level dissemination primitives which do not overwhelm the overlay, i.e. which are efficient, and which are also reliable. Building such communication primitives in a reliable manner would increase the confidence regarding their behavior prior to deploying them in real settings. In order to come up with real efficient primitives, we take advantage of the underlying geometric topology of the overlay network and we also model the way peers communicate with each other. Our objective is to design and prove an efficient (in terms of messages and execution time) and reliable broadcast algorithm for CAN-like P2P networks. To this aim, this year, we realized the following:

- publication in FASE 2013 of a formalisation, in Isabelle/HOL, of CAN-like P2P networks [15]. Thank to this work, we proved that there exist a broadcast algorithm that does not produce any duplicated message in those networks. A first naive algorithm was exhibited to prove it.
- design and publication of an optimal broadcast algorithm for CAN-like P2P networks in OPODIS 2013 [20]. The solution we have proposed is proven to be correct, optimal in terms of number of messages, and also efficient, as it provides a good parallelization during the dissemination.

We are also investigating new algorithms to efficiently build a SON when the peer involved already have data. Most of the work on SONs assume that new peers joining the network will arrive without data and thus get assigned a random position. However, if they already have data, they will have to send them to other peers, depending on the key space they are responsible of. In 2013, we continued on the tracks investigated in 2012:

- We proposed a first version of new join algorithms which try to allocate key sub-spaces to peers so that the amount of data that needs to be moved is minimal. An expected benefit of this work is that it should allow for fast and efficient reconstruction of a SON in case of a crash, without having to use distributed snapshots.
- We have conducted preliminary experiments which shows a reduction of data transfer between 20% and 90%.

6.2.2. Open Virtual Machines Placement Algorithms

Participants: Fabien Hermenier, Vincent Kherbache, Huynh Tu Dang.

Clients of IaaS providers are looking for dependable infrastructures that can cope with their SLA requirements. To stay attractive, a cloud must then rely on a Virtual Machine (VM) placement algorithm with features matching wrt the SLAs expectations. These constraints are however very specific to each of the tenants but also the infrastructure. They also cover a large range of concerns (reliability, performance, security, energy-efficiency, ...) that are continuously evolving according to new trends and new technologies. To address these issue, we advocate for a flexible VM placement algorithm that can be specialized through plugins to address new concerns.

This year, we first validate our approach with BtrPlace, a composable VM placement algorithm built over Constraint Programming [9]. The usage of Constraint Programming makes placement constraints independent of each other. New constraints can be added without changing the existing implementation. The expressivity of BtrPlace has been verified by implementing more than 20 placement constraints that reproduce, extend but also bring new meaningful restrictions on the VM placement with regards to constraints available in commercial placement algorithm. Each constraint was implemented by an average of 30 lines of Java code. An experienced developer implemented some of the them in half a day, while external developers, without any background in CP, have implemented constraints related to power efficiency [43].

Secondly, we exhibited a lack of reliability in the common approach to address placement constraints in some algorithms. Usually, a constraint controls the VM placement only at the end of the reconfiguration process and ignores the datacenter intermediary states between the beginning and the end of the reconfiguration process. In [11], we advocated that this discrete approach is not sufficient to satisfy the SLAs continuously as an uncontrolled actions schedule may indeed lead to temporary violations. We relied on the flexibility provided by BtrPlace to exhibit these violations and to propose *continuous constraints* to control the quality of service at any moment. We implemented preliminary version of continuous constraints and confirmed they improve the datacenter reliability by removing any temporary violations.

6.2.3. GPU-based High Performance Cloud Computing

Participants: Michael Benguigui, Françoise Baude, Fabrice Huet.

To address HPC, GPU devices are now considered as unavoidable cheap, energy efficient, and very efficient alternative computing units. The barrier to handle such devices is the programming model: it is both very fine grained and synchronous. Our long term goal is to devise some generic solutions in order to incorporate GPU-specific code whenever relevant into a parallel and distributed computation. The first step towards this objective was to gain some insight on how to efficiently program a non trivial but well known algorithm. Our previous work [40] highlights the necessity to target a GPU rather than distributed CPUs to provide the same performance level. By this way we price complex American basket options through the Picazo pricing algorithm, in the same order of time than a CPU cluster implementation on a 64-core cluster. This year, we achieved the following tasks

- We proposed a multi GPU based implementation of this method, allowing pricing time to fall below 1 hour on 18 GPUs, for a 40-assets American option [14].
- We are currently designing a task dispatching model to load balance tasks in a CPU-GPU cluster. This will allow us to drastically lower the overall computation time of a portfolio estimation, and moreover, the computation time of the Monte Carlo value at risk of a portfolio of complex assets.

6.2.4. MapReduce Based Frameworks for Big Data

Participants: Fabrice Huet, Ge Song.

MapReduce is a programming model which allows the processing of vast amounts of data in parallel, on a large number of machines. It is particularly well suited to static or slow changing set of data since the execution time of a job is usually high. However, in practice data-centers collect data at fast rates which makes it very difficult to maintain up-to-date results. To address this challenge, we propose in [25] a generic mechanism for dealing with dynamic data in MapReduce frameworks. Long-standing MapReduce jobs, called *continuous Jobs*, are *automatically* re-executed to process new incoming data at a minimum cost. We present a simple and clean API which integrates nicely with the standard MapReduce model. Furthermore, we describe cHadoop, an implementation of our approach based on Hadoop which does not require modifications to the source code of the original framework. Thus, cHadoop can quickly be ported to any new version of Hadoop. We evaluate our proposal with two standard MapReduce applications (WordCount and WordCount-N-Count), and one real world application (RDF Query) on real datasets. Our evaluations on clusters ranging from 5 to 40 nodes demonstrate the benefit of our approach in terms of execution time and ease of use.

Another important point is the difficulty to predict the performance of a MapReduce job. This is particularly important when using pay-as-you-go resources such a Cloud. We have proposed a simple framework to predict the performance of Hadoop jobs. It is composed of a dynamic light-weight Hadoop job analyzer, and a prediction module using locally weighted regression methods. Our framework makes some theoretical cost models more practical, and also fits well with jobs and clusters diversity. It can also help those users who want to predict the cost when applying for an on- demand cloud service.

6.3. Application Domains

6.3.1. Publish-Subscribe in Distributed Environments

Participants: Françoise Baude, Fabrice Huet, Laurent Pellegrino, Bastien Sauvan, Iyad Alshabani, Maeva Antoine, Amjad Alshabani.

In the context of the FP7 STREP PLAY and French SocEDA ANR research projects we have developed a middleware dubbed EventCloud (Section 5.5). This last aims to store and retrieve Resource Description Framework (RDF) data but also to relay them to interested parties through a publish/subscribe layer that allows the formulation of content-based subscriptions. Content-based subscriptions are automatically deduced from more complex rules deployed onto a Complex Event Processing engine, the aim of these CEP rules being to trigger new (complex) events after detecting interesting situations [24]. The EventCloud architecture relies on a CAN structured P2P overlay network we initially designed and implemented for the former SOA4ALL FP7-IP project [44].

This year we continued to improve the performances of the EventCloud middleware and its usability as a standalone component but also as a component integrated within the previous projects' platform. Concretely, we proposed a new publish/subscribe matching algorithm for RDF events made of several related RDF triples, that was thoroughly presented in [31] and [22]. To further improve performance, we pursue some efforts to finalize the usage of the newest multi-active object library (cf. Section 6.1.1). Also, to handle more efficiently multicast messaging, we replaced our initial and naive solution with the optimal one presented in Section 6.2.1. Finally, we proposed a solution for managing multiple EventCloud instances on various cloud platforms, especially for the integration of our middleware in the PLAY and SocEDA platforms (whose latest assessment can be found in [32]). Details about EventCloud management are provided in [29].

Since RDF resources have the property to be poorly balanced, we are also investigating new algorithms that decrease load imbalance for events and data.

6.3.2. Large-scale Simulation Platform: Techniques and methodologies

Participants: Olivier Dalle, E. Mancini, Damian Vicino.

In the domain of simulation techniques and methodologies, this year, we conducted research in the two following areas:

Distributed Network Simulation NetStep[16], is a prototype we developed for the distributed simulation of very large scale network simulations, such as the simulation of peer-to-peer applications. We use simulation micro-steps as a means for optimizing the overlap of communications and computations, without changing the original event-driven model. As a consequence, NetStep allows for the reuse of unmodified existing sequential simulators for building large-scale distributed simulations: the overall simulation is divided both in time and space, into a large number of simulation micro-steps, each of which being executed by a legacy sequential simulator. By choosing the time-step smaller than the minimal look-ahead due to communications, we avoid the need for synchronization between logical processes (LPs) during the simulation. Instead, the simulated communications become inputs and outputs of the simulation micro-steps, and are routed in parallel between LPs by a NetStep dedicated entity. Our prototype is based on the SimGrid sequential simulator.

Discrete Time Representation The representation of time in simulations is a long standing issue, for which many solutions and formalisms have been proposed. However, once the formalism is chosen, the implementation of the time representation is still a non trivial problem: Integer values have a limited range and require the selection of a minimal fixed step that does not support well the multi-scale models; Floating Points numbers have numerous limitations and hidden effects such as rounding due to quantization; those issues result in inaccuracies or even timing errors. In collaboration with our partner in the DISSIMINET Associated Team, we have started a new research on this topic. This research will be released in the form of a new Discrete Event Simulation engine library for the DEVS formalism, designed to fully exploit the 2011 C++ standard; it is candidate for inclusion in the BoostC++ Libraries.

AYIN Team

6. New Results

6.1. Markov Random Fields

6.1.1. Hierarchical multitemporal and multiresolution classification in remote sensing imagery

Participants: Ihsen Hedhli, Josiane Zerubia [contact].

This activity was conducted in collaboration with Dr. Gabriele Moser and Prof. Sebastiano B. Serpico (Department of Electrical, Electronic, and Telecommunications Engineering and Naval Architecture, DITEN, University of Genoa) [<http://www.unige.it>] with partial financial support from CNES [<http://www.cnes.fr>].

Markov random field (MRF), hierarchical classification, satellite image time series

The capability to monitor the Earth's surface, and especially urban and built-up areas, for environmental disasters such as floods or earthquakes, and to assess the ground impact and damage caused by such events, play important roles from multiple social, economic, and human viewpoints. Current and forthcoming satellite missions for Earth observation (EO; e.g., Pleiades, COSMO-SkyMed, TerraSAR-X, Sentinel) possess huge potential for such applications, as they allow a spatially distributed and temporally repetitive view of the monitored area at the desired spatial scales. In this framework, accurate and time-efficient classification methods using time series are especially important tools for supporting rapid and reliable assessment of the ground changes and damage induced by a disaster, in particular when an extensive area has been affected. Given the huge amount and variety of data available, the main difficulty is to find a classifier that takes into account multi-band, multi-resolution, multi-date, and possibly multi-sensor data.

This research addresses the problem of supervised classification at multiple spatial resolutions for multiple dates. The approach is based on the extension of recent methods proposed by DITEN and/or AYIN [4], [5], [6]. These methods focus on a supervised Bayesian classifier that combines joint class-conditional statistical modeling and a hierarchical Markov random field. The key idea of the proposed method is to combine the multiresolution modeling capabilities of this previous technique with a model for the temporal correlation among distinct images in a time series. For this purpose, a hierarchical spatio-temporal Markov random field model has been proposed that is aimed at fusing the pixel-wise, neighborhood, multiresolution, and temporal information associated with the input time series. Pixel-wise information is characterized through separate statistical modeling for each target class (e.g., vegetation, urban, etc.) by using a finite mixture model, estimated using a modified stochastic expectation maximization algorithm. Such a model is well suited to dealing with heterogeneous classes, and each mixture component may reflect the contribution of the different materials contained in a given class. At each considered resolution, the different input bands are statistically combined by using multivariate copulas, and the resulting statistical pixel-wise model is integrated in a hierarchical Markov random field based on a quad-tree structure. Among the different algorithms employed in the literature, we chose to use an exact estimator based on the marginal posterior mode (MPM). Specifically, a new formulation of MPM is developed to formalize, within the aforementioned hierarchical model, a 'cascade' multi-date decision rule. Such a classifier is sufficiently flexible to take into account different types of data (e.g., multispectral, panchromatic, synthetic aperture radar). The method is being experimentally validated with data acquired over a given area at different resolutions (e.g., multiresolution Pleiades images), directly integrated at the different levels of the cascade hierarchical model. An example of a classification result is illustrated in Fig. 1. Here, Pleiades multiresolution images (panchromatic resolution: 50 centimeters and multispectral resolution: 2 meters) acquired over Port-au-Prince quay (Haiti) on two different dates are considered. Spatially disjoint training areas were manually annotated. The classification has been performed with respect to 5 main classes: urban areas, natural landscape, sand, containers, and wet areas. A visual analysis of the resulting map suggests that the proposed approach achieves remarkable accuracy.



Figure 1. Right: Initial optical image of Port-au-Prince (Haiti) (©CNES, 2013). Left: Classification map obtained with the proposed multi-temporal hierarchical method for the 5 classes (blue: wet areas; green: vegetation; red: urban areas; yellow: sand; purple: containers).

6.1.2. A multi-layer Markov model for change detection in temporally separated aerial image pairs

Participants: Praveer Singh, Josiane Zerubia [contact].

This work was carried out in collaboration with Prof. Zoltan Kato from Institute of Informatics, University of Szeged, Hungary. [<http://www.inf.u-szeged.hu/~kato/>].

Multilayer Markov Random Fields (MRF), Histogram of Gradients (HOG), change detection, graph-cut optimization, aerial / satellite images.

In the proposed approach, we have tried to include both texture as well as pixel level information to build a three layer Markov model using the *Histogram of Oriented Gradients (HOG)* and the *Gray Level Difference* features on the topmost and bottommost layer respectively. Using a ground truth (GT) mask defined manually by an expert for each of the image pairs in the data set (obtained from the Hungarian Institute of Geodesy, Cartography and Remote Sensing), we employ a supervised technique to mark the initial set of pixels / sites as foreground or background. On the basis of the *HOG difference* and the *Gray level difference* feature vector corresponding to all the pixels in the image pair, a probability density function is fitted individually for the binary label set comprising of foreground and background labels using the GT. The probabilistic estimate is calculated using one training image pair for each data set. Using this probabilistic measure, a negative log likelihood is computed for each pixel (for both the features as well as the binary label set) which is then passed to the energy function of the proposed 3-layer MRF model. The final segmentation is obtained by minimizing the energy using a graph-cut algorithm, and subsequently a final foreground and background labelling is obtained over the combined layer. Figure 2, shows aerial image pairs, one of them captured in 1984 by FOMI, Hungary (a) and the other one by GoogleEarth in 2007 (c). (b) is the ground truth and (d) is a combination of the hierarchical MRF based change detection (in red), ground truth (in green) and changes detected correctly (in yellow).

6.1.3. Graph-cut model for spectral-spatial classification of hyperspectral images

Participants: Aakanksha Rana, Yuliya Tarabalka [contact].

Hyperspectral images, graph cut, multi-label alpha expansion, contextual information, energy minimization

The very high spatial and spectral resolution of the last generation of remote sensors provides rich information about every pixel in an image scene, hence opening new perspectives in classification, but also presenting the challenge of analysing high data volumes. While pixel-wise classification methods analyze each pixel independently, classification results can be significantly improved by including spatial information in a classifier.

In this work, we proposed a spectral-spatial method for hyperspectral image classification based on a graph cut. The classification task is expressed as an energy minimization problem on the spatio-temporal graph of image pixels, and is solved by using the graph-cut α -expansion approach. The energy to optimize is computed as a sum of data and interaction energy terms, respectively. The data energy term is computed using the outputs of the probabilistic support vector machines classification. The second energy term, which expresses the interaction between spatially adjacent pixels in the eight-neighborhood, is computed by using dissimilarity measures between spectral vectors, such as vector norms, spectral angle map, or spectral information divergence. The performance of the proposed method was validated on hyperspectral images captured by the ROSIS and the AVIRIS sensors. Figure 3 compares classification results obtained by applying support vector machines and the proposed approach for the ROSIS hyperspectral image acquired over the University of Pavia. The new method yields higher classification accuracies when compared to the recent state-of-the-art approaches.

6.2. Marked point processes

6.2.1. Marked point process models for boat extraction from high resolution remotely sensed optical images

Participants: Paula Craciun, Josiane Zerubia [contact].



Figure 2. Change detection in an aerial image pair using a hierarchical MRF. a) Aerial image captured in 1984 by ©FOMI; b) Ground truth; c) Aerial image captured by ©GoogleEarth in 2007; d) Combination of the hierarchical MRF based change detection (in red), ground truth (in green), and changes detected correctly (in yellow).



Figure 3. Hyperspectral image of the University of Pavia. (a) Ground-truth (b) Support vector machines classification map. (c) Graph-cut classification map.

This work was done in collaboration with Dr. Mathias Ortner (ASTRIUM EADS) [<http://www.astrium.eads.net>] and Prof. Pierre del Moral (ALEA team, Inria Bordeaux).

Stochastic geometry, Markov model, detection, parallel algorithm

Marked point process models have been successfully applied to object extraction problems in high resolution optical images, ranging from tree crown or road extraction to flamingo or crowd counting. We try to model the problem of boat detection and counting in harbors. The difficulty of this problem resides in the particular distribution of the objects. The model consists of two energy terms: a data term, which reflects the model's fidelity to the input image, and a prior term containing knowledge about the objects to be extracted. The model relies on a high number of parameters and is computationally intensive. The purpose of this research is to extend a previously developed marked point process model of ellipses and make it more computationally manageable. In particular, we add a preprocessing step in which we determine the global and local direction of the objects [8], [17]. Additionally, segmentation of land and water areas is implemented as a preprocessing step. Boat extraction results are shown in Figure 4. Finally, we implement an improved parallel sampler, thereby drastically improving computation times.



Figure 4. Boat extraction in a harbor using a marked point process model (a) harbor image ©CNES; (b) extraction results.

6.2.2. *Parameter estimation for automatic object detection in very high resolution optical images*

Participants: Aurélie Boisbunon, Josiane Zerubia [contact].

This work was partially funded by the French Space Agency CNES [<http://www.cnes.fr>].

Markov model, Monte Carlo method, evolutionary algorithm, optimization, image processing, detection

The main goal of this work is to study parameter estimation for several marked point processes. Currently, the parameters of such models are estimated by a Stochastic Expectation and Minimization (SEM) algorithm, which is computationally expensive. We will investigate and propose new parameter estimation techniques, based on Randomized Quasi-Likelihood and evolutionary algorithms, for the parameters of the probability density of a marked point process. The goal is to improve computation times with respect to SEM while maintaining similar accuracy. The first application envisioned is boat detection for harbor activity monitoring (see Figure 5).



Figure 5. Harbor activity monitoring. ©CNES

6.2.3. *Wrinkle detection using a marked point process*

Participants: Seong-Gyun Jeong, Yuliya Tarabalka, Josiane Zerubia [contact].

Skin image processing, wrinkle detection, line detection, marked point process, RJMCMC

We developed a novel wrinkle detection algorithm using a marked point process (MPP). Since wrinkles are the most important visual features of aging, automatic wrinkle detection algorithm can have many applications, such as the evaluation of cosmetic products, age estimation, and aging synthesis. In order to detect wrinkles of arbitrary shape, we represent wrinkles as a set of small line segments. Note that each line segment consists of a length and an orientation. A stochastic wrinkle model density exploits the local edge profile and constrains the spatial placement of adjacent lines. To maximize the model density, we employ a reversible jump Markov chain Monte Carlo (RJMCMC) sampler. A state of the Markov chain corresponds to a wrinkle configuration, and it is updated according to the acceptance ratio of sub-transition kernels: line segment births and deaths, and an affine transformation kernel. The transition kernels perturb the Markov chain by adding, removing, or modifying a wrinkle segment in the current configuration. In addition, an acceleration scheme has been developed for the RJMCMC sampler that enforces the connectivity of line segments. RJMCMC with acceleration reduces mixing time and improves detection accuracy as well.

Figure 6 compares wrinkle detection results simulated by random walk and the proposed acceleration scheme. The proposed algorithm faithfully detects wrinkles as smoothly connected lines. In addition, Figure 6 (d) plots the energy as a function of the number of iterations. It shows that the proposed acceleration method reaches a lower energy more rapidly than the random walk method.

6.3. Shapes and contours

6.3.1. Shape reconstruction from lidar data

Participant: Ian Jermyn [contact].

This work is being done in collaboration with Dr. Stuart Jones, Dr. Jochen Einbeck, and PhD student Thomai Tsiftsi of Durham University, UK [<https://www.dur.ac.uk>].

sand body, petroleum, shape, submanifold,

The cross-sectional shapes of ‘sand bodies’, ancient underground river channels filled with sediment, are of great interest in geology, and to the petroleum industry, because the shape is strongly correlated with the nature of the sediment, and in particular with its porosity, which in turn helps determine the volume fraction of crude oil contained in the sand body. The geological literature, however, only discusses simple characterizations of these shapes, and there is much room for improvement. This project aims to build probabilistic models of the cross-sectional shapes of sand bodies based on lidar point cloud data gathered from surface-projecting sand bodies by geologists in the field. Such models, when built, can be used to test the current geological classification of sand bodies, to generate new and geologically relevant classes, and to build functional models of the connection between sand body shape and oil yield.

Current work is focused on extracting reliable cross-sectional shapes from the lidar data (see Figure 7), a difficult task in itself since the sand bodies are frequently occluded or otherwise incomplete. Bayesian inference based on parameterized models of shape suggested by the current geological classification are used for this purpose. Since sand body shapes are concentrated near a low-dimensional submanifold of shape space, these models will later be extended using techniques such as mixtures built on principal curves, adapted to curved manifolds, in order to find and characterize this submanifold.

6.3.2. Riemannian metrics on spaces of curves and surfaces

Participant: Ian Jermyn [contact].

This work is being done in collaboration with Prof. Anuj Srivastava of Florida State University [<http://www.fsu.edu>].

Shape, Riemannian metric, elastic, curve, surface, functional data, alignment



Figure 6. Comparison of wrinkle detection results using different simulation procedures: (b) random walk and (c) the proposed acceleration scheme. Energy as a function of the number of iterations is plotted in (d).



Figure 7. Left: a point cloud containing a sand body extracted from a larger cloud. Right: cross-sectional shape derived from the point cloud.

Statistical shape modelling has many applications in image processing and beyond. One of the key problems in this area is to develop and understand measures of shape similarity. One approach uses Riemannian metrics defined on 'shape space', the quotient of spaces of sphere or disc embeddings by similarities or other geometric group, and the diffeomorphism group of the sphere or disc. These metrics are defined by Riemannian metrics on the space of embeddings on which the transformation groups act by isometries, and so attention is focused on understanding such metrics and their properties.

Current work is focused on two areas. The first is on classifying and describing the diffeomorphism-invariant metrics on function spaces (shapes in one dimension) that satisfy additional desiderata useful in different applications, with particular application to function alignment. The second is on generalizing to surfaces the elastic metric much used in the case of curves, and in finding surface representations that permit analytic results to be derived, or that simplify computations, in the same way that the square root velocity representation simplifies computations involving the elastic metric on curves (see Figure 8).



Figure 8. Top: interpolating surfaces based on a previous Riemannian metric. Bottom: interploating shapes based on the generalized elastic metric.

6.3.3. Sampling methods for random field models of shape

Participant: Ian Jermyn [contact].

Part of this work is being done in collaboration with Prof. Zoltan Kato and PhD student Csaba Molnar of the University of Szeged, Hungary [<http://www.inf.u-szeged.hu/~kato/>], and part in collaboration with PhD student Michael Racovitan of Durham University, UK [<https://www.dur.ac.uk>].

Shape, long range interaction, Markov random field, phase field, contour, learning, wavelet

The detection and segmentation of objects from images is a problem with innumerable applications in many domains. Probabilistic models of shape, used as prior distributions in the inference process, are a necessity in solving any nontrivial instance of this problem. In many cases of importance, the shapes to be modelled cannot be treated efficiently, or at all, with current techniques, for example when multiple instances of an object must be segmented. The overall goal of this project is to develop a general shape modelling methodology capable of dealing with these difficult cases, as well as more traditional instances of the problem.

Recent algorithmic work has focused on developing efficient sampling methods for the models, for use in parameter and model learning. The models, whether expressed in terms of shape boundaries, phase fields, or binary fields, contain many long-range frustrated interactions, and hence are not amenable to standard techniques. Simplifications of the interaction structure using adapted wavelet bases, and re-expressions of the models using varieties of Hubbard-Stratanovich transformation are two directions being explored.



Figure 9. A typical result on an image of lipid cells.

6.3.4. Multiple-instance object detection via a third-order active contour shape model

Participants: Ikhlef Bechar, Ian Jermyn, Josiane Zerubia [contact].

This work was funded by the EADS Foundation [<http://www.fondation.eads.com>].

Object detection, multiple objects, shape, invariance, prior, higher-order active contour (HOAC), energy minimization

Recent modelling work has focused on generalizing the higher-active contour methodology to families of shapes whose members consist of an arbitrary number of object instances, each of which is similar to a given reference shape. This means finding energies on the space of regions that possess low-energy local minima corresponding to an arbitrary number of instances of the reference shape. To this end, we have studied a family of fourth-order energy functionals on regions based on a kernel given in closed form as a function of the reference region. The energy has, amongst its global minima, regions consisting of an arbitrary number of well-separated instances of the reference shape, each under an arbitrary Euclidean transformation, thereby eliminating the need to estimate group-valued ‘pose’ parameters. It may be combined with a likelihood energy, and the result minimized using gradient descent, speeded up by use of the Fourier domain. Although problems still remain, a series of experiments on both synthetic and real images has demonstrated the feasibility of the approach (see Figure 10).



Figure 10. Detection of a shape in a noisy infrared image (SNR = 5dB): (top row) without using prior shape knowledge, and (bottom row) using the proposed fourth-order prior shape model. First column: initialization; second column: intermediate contour; third column: final contour; fourth column: segmentation.

6.4. Shapes in time

6.4.1. Graph-based model for multitemporal segmentation of sea ice floes from satellite data

Participants: Claudio Price González, Yuliya Tarabalka [contact].

This work has been done in collaboration with Dr. Ludovic Brucker (NASA GSFC, USA) [<http://www.nasa.gov>].

Multitemporal segmentation, region growing, MODIS, sea ice floes

Automated segmentation of the evolution of sea ice from satellite images would allow scientists studying climate change to build accurate models of the sea ice meltdown process, which is a sensitive climate indicator. In this work, we proposed a new method which uses shape analysis and graph-based optimization to segment a multiyear ice floe from time series of satellite images [13]. The new approach combines data from two instruments onboard the NASA Aqua satellite, enabling several measurements per day over the Earth's polar regions: Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E); and Moderate-Resolution Imaging Spectroradiometer (MODIS). The method performs best merge region growing, followed by energy minimization on the image graph, where the energy consists of two terms describing the floe shape (shape term) and the gradient between the floe and the background (data term), respectively. We validated the performance of the proposed method for segmentation of a shrinking ice floe from a sequence of AMSR-E and MODIS images acquired in August–October 2008 (see Figure 11). The results obtained showed both the effectiveness of the proposed approach and its robustness to low-contrast data.

6.4.2. Enforcing monotonous shape growth or shrinkage in video segmentation

Participant: Yuliya Tarabalka [contact].

This work has been done in collaboration with Dr. Guillaume Charpiat (STARS team, Inria-SAM), Dr. Bjoern Menze (Computer Vision Laboratory at ETH Zurich and Asclepios team at Inria-SAM), and Dr. Ludovic Brucker (NASA GSFC, USA) [<http://www.nasa.gov>].

Video segmentation, graph cut, shape analysis, shape growth

Automatic segmentation of objects from video data is a difficult task, especially when image sequences are subject to low signal-to-noise ratio or low contrast between the intensities of neighboring structures. Such challenging data are acquired routinely, for example, in medical imaging or satellite remote sensing. While individual frames can be analyzed independently, temporal coherence in image sequences provides a lot of information not available for a single image. In this work, we focused on segmenting shapes that grow or shrink monotonically in time, from sequences of extremely noisy images.

We proposed a new method for the joint segmentation of monotonically growing or shrinking shapes in a time sequence of images with low signal-to-noise ratio [15]. The task of segmenting the image time series is expressed as an optimization problem using the spatio-temporal graph of pixels, in which we are able to impose the constraint of shape growth or shrinkage by introducing unidirectional infinite-weight links connecting pixels at the same spatial locations in successive image frames. The globally-optimal solution is computed with a graph-cut algorithm. The performance of the proposed method was validated on three applications: segmentation of melting sea ice floes; of growing burned areas from time series of 2D satellite images [16]; and of a growing brain tumor from sequences of 3D medical scans. In the latter application, we imposed an additional inter-sequences inclusion constraint by adding directed infinite-weight links between pixels of dependent image structures. Figure 12 shows a multi-year sea ice floe segmentation result. The proposed method proved to be robust to high noise and low contrast, and to cope well with missing data. Moreover, it showed linear complexity in practice.

6.5. Other detection approaches

6.5.1. Illumination modeling and chromophore identification in dermatological images for skin disease analysis

Participants: Zhao Liu, Josiane Zerubia [contact].



Figure 11. Comparison of results for the MODIS image sequence acquired in August-October 2008. Manual segmentation of the ice floe contour is shown in green, hierarchical step-wise optimization result in red, and the new graph-based approach in blue.



Figure 12. Top: MODIS images for four time moments (days 230, 233, 235 and 267 of 2008, respectively). Bottom: corresponding aligned images with segmentation contours (in red). Manual segmentation is shown in green.

This work is part of the LIRA Skin Care Project, which includes four key partners: Philips R&D [<http://www.research.philips.com>], CWI (Netherlands) [<http://www.cwi.nl>], Inria (France), and Fraunhofer Institutes (Germany) [<http://www.fraunhofer.de/en.html>].

Chromophore identification, illumination modeling, skin disease analysis, dermatology

Skin color is an important characteristic for the accurate diagnosis and grading of cutaneous lesions by experienced dermatologists in clinical practice. However, the visual perception of skin color is not only a function of the major chromophores (melanin and hemoglobin) underneath the skin surface, but is also affected by external illumination and the spectral responses of imaging detectors. Skin color representation in a specific color space (e.g. RGB and its transformations) is not a genuine physical quantity. It sometimes fails to provide precise information about the concentrations of cutaneous chromophores, and is easily influenced by external imaging factors. As a result, conventional colorimetry may not properly describe the underlying histological content of skin, and hence tends to yield less trustworthy results when applied directly for skin disease analysis.

Building on a previous study that considered human skin as a diffuse reflectance surface, our work models human skin as having specular and diffuse reflectance, leading to a novel illumination correction method. Based on this method, we have developed a new scheme for chromophore identification from dermatological photographs. The algorithm has three steps. First, specular reflectance is separated from diffuse reflectance in the original skin images through specular pixel localization and image interpolation using a nonlinear weighted averaging process. Second, the resultant diffuse reflectance component is decomposed into a base layer and a detail layer. The base layer, representing low-frequency illumination and shading effects, is approximated by polynomial curve fitting using an initial illumination map using an adaptive bilateral filter as a prior. The detail layer, primarily containing high-frequency chromophore reflectance, can then be calculated by subtracting the base layer from the corresponding diffuse spectral band in logarithmic form. Finally, by incorporating knowledge of chromophore absorption characteristics, melanin and hemoglobin densities are identified using the detail layers from different spectral channels [11].

For algorithm evaluation, the method was applied to two skin disease analysis problems: computer-aided melanoma diagnosis [11] and automatic acne detection [12]. For melanoma diagnosis, 201 conventional RGB skin lesion images (62MMs, 139 benign nevi (BN)) were collected from free public databases (<http://www.dermquest.com/>, <http://www.dermis.net/>) to form an experimental data set. Figure 13 -(I) shows an example of a superficial spreading melanoma with obvious horizontal shading effects, and the corresponding experimental results. It is clear that the proposed algorithm successfully removed the imaging artifacts from the original skin lesion photographs.

For acne detection, a set of 50 challenging images were tested as a qualitative evaluation to demonstrate the usefulness of the proposed method. Automatic acne segmentation is performed using an MRF model based on chromophore descriptors. Figure 13 -(II) shows one acne example captured in an uncontrolled environment from a free public database (<http://www.dermnetz.org/>). The detected acne areas are highly consistent under visual inspection, and the inflammatory acne can be distinguished from hyperpigmentation by comparing the average values of the melanin and hemoglobin indices.



Figure 13. Examples of different types of skin disease requiring shading removal and chromophore identification: (I-a) Original melanoma image; (I-b) Corrected melanoma image; (I-c) Melanin index map of image (I-a); (I-d) Hemoglobin index map of image (I-a); (I-e) Two-class segmentation results from Otsu's method on the original melanoma image (black line) and the corrected melanoma image (blue line), respectively; (II-a) Original acne image; (II-b) Melanin index map of image (II-a); (II-c) Hemoglobin index map of image (II-a); (II-d) Acne segmentation result using an MRF model, highlighting inflammatory acne (blue line) and hyperpigmentation (black line), respectively.

GRAPHIK Project-Team

6. New Results

6.1. Ontology-Based Query Answering with Existential Rules

Participants: Jean-François Baget, Fabien Garreau, Mélanie König, Michel Leclère, Marie-Laure Mugnier, Swan Rocher, Michaël Thomazo.

Note that for this section, as well as all sections in New Results, participants are given in alphabetical order.

This year we continued to work on the existential rule framework in the context of Ontology-Based Query Answering (a.k.a. Ontology-Based Data Access, OBDA). See the 2011-2012 activity reports for details on this framework (a.k.a. Tuple-Generating Dependencies or Datalog+/-). The ontology-based query answering issue consists in querying data while taking into account inferences enabled by an ontology. This ontology is here described by existential rules, a very expressive formalism which generalizes the lightweight description logics used for OBDA (e.g. the tractable fragments of the Semantic Web language OWL 2).

From 2009 to 2011, we mainly investigated decidability and complexity issues. In 2012, we tackled the next step, which consists in developing algorithms with good theoretical properties (they should at least run in the “right” worst-case complexity class) and with good performance in practice. There are two main ways of processing rules, namely forward chaining and backward chaining, which are also known as “materialization” and “query rewriting”. In forward chaining, rules are applied to enrich the initial data and query answering can then be solved by evaluating the query against the “saturated” database (as in a classical database system, i.e., forgetting the rules). Backward chaining process can be divided into two steps: first, the initial query is rewritten using the rules into a first-order query (typically a union of conjunctive queries, UCQ); then the rewritten query is evaluated against the initial database (again, as in a classical database system).

In 2013, on the one hand we focussed on the improvement of query rewriting algorithms, on the other hand we began to investigate extensions of our framework.

6.1.1. Improvement of Query Rewriting Algorithms

The advantage of the query rewriting approach is that the data are not modified (hence no write access permission is required and the data do not grow; moreover, there is no materialization that would need to be updated when data change). However, the practicability of this approach is questionable due to (1) the weak expressivity of classes for which efficient rewriters have been implemented, and (2) the large size of rewritings using UCQ.

With respect to the first point, we improved the algorithm designed in 2012. This algorithm accepts as input any set of existential rules and stops if this set of rules fulfills so-called finite unification set (fus) property, meaning that the set of rules allows to rewrite any query as a first-order query, e.g. a UCQ (this property is not true in general, where no finite rewriting may exist). We also studied properties of rewriting operators that ensure the correctness and the termination of a generic breadth-first rewriting algorithm and analyzed some operators with respect to these properties.

- *Work published in IJCAI 2013 [37] and RR 2013 (Rules and Web Reasoning) [36]*

With respect to the second point, we defined semi-conjunctive queries (SCQs), which are a syntactical extension of conjunctive queries. We designed and implemented an algorithm called Compact, which computes sound and complete rewritings of a conjunctive query in the form of a union of SCQs (USCQs). As in the above work, any kind of existential rules can be considered, however the algorithm is ensured to stop only for fus rules. First experiments show that USCQs are both very efficiently computable and more efficiently evaluable than their equivalent UCQs.

- *Work published in IJCAI 2013 [41]*

6.1.2. Ongoing Work: Extensions of the Framework

Inconsistent-tolerant query answering. It may be the case that the data are inconsistent with the ontology, specially when there are several data sources. The classic logical framework becomes inappropriate since an inconsistent logical theory entails everything. Therefore, inconsistency-tolerant semantics have been defined to get meaningful answers. These semantics are based on the notion of repairs, which are maximal subsets of the data consistent with the ontology. In the most natural semantics, a tuple is an answer to the query if it is an answer in each repair. This issue is relevant to Pagoda and Qualinca, two ANR projects respectively started in 2013 and 2012 (see Section 8.1). Swan Rocher’s master thesis was devoted to a query answering algorithm in this framework, where the ontology is described by existential rules and negative constraints.

Existential Rules with non-monotonic negation. Non-monotonic negation is very useful for modeling purposes. We added non-monotonic negation to existential rules, under stable model semantics. This brought us close to logic programs considered in the area called Answer Set Programming. First results were obtained on the semantics and decidability of query answering with these rules. This work is part of ASPIQ project started in 2013 (see Section 8.1).

- Paper curenly submitted to an international conference.

6.1.3. Others

Michael Thomazo defended his PhD thesis entitled “Conjunctive Query Answering Under Existential Rules —Decidability, Complexity, and Algorithms” (Oct. 2013). The main contributions of this thesis are the following: first, a unified view of the currently known existential rule classes ensuring decidability of query answering, together with a complexity analysis and a worst-case optimal algorithm for a new generic class, which generalizes a family of very expressive decidable classes (see the gbts class in 2012 activity report); second, a generic algorithm for query rewriting, which overcomes some causes of combinatorial explosion that make classical approaches inapplicable.

- See the PhD thesis [15] and the extended abstract published in IJCAI 2013 [42].

The journal version extending the papers at IJCAI 2011 and KR 2012, in collaboration with Sebastian Rudolph (TU Dresden), is still in preparation but almost finished (postponement due to the addition of complementary results).

6.2. Reasoning with Imperfect Information and Priorities

Participants: Madalina Croitoru, Jérôme Fortin, Souhila Kaci, Tjitze Rienstra, Rallou Thomopoulos.

6.2.1. Monotonic and Non-monotonic Inference for Abstract Argumentation

An argumentation framework (or framework, for short) consists of a set of arguments, whose content may be left unspecified, together with an attack relation encoding conflict between arguments. Given a framework, a semantics specifies which sets of arguments (called extensions) are rationally acceptable. This formalism captures many different types of reasoning considered in the area of AI. In many applications, a framework somehow represents (part of) an agent’s belief state. Beliefs are then formed on the basis of acceptable sets of arguments. For example, a ‘grounded reasoner’ forms beliefs on the basis of the framework’s grounded extension, a ‘preferred reasoner’ on the basis of the preferred extensions, and so on. There is a problem with this account, however. Two different argumentation frameworks may be considered equivalent as soon as they lead to the same extensions. A more appropriate notion of equivalence is strong equivalence. Given a semantics, two frameworks are said to be strongly equivalent if their extensions are the same given every possible addition of new arguments and attacks. But still, it leaves open the question of how to form beliefs on the basis of a framework, so that different frameworks can be meaningfully distinguished, even if their extensions are the same. We addressed this problem and presented a new approach to reasoning about the outcome of an argumentation framework, where an agent’s reasoning with a framework and semantics is represented by an inference relation defined over a logical labeling language. We first studied a monotonic type of inference which is, in a sense, more general than an acceptance function, but equally expressive. In

order to overcome the limitations of this expressiveness, we studied a non-monotonic type of inference which allows counterfactual inferences. We precisely characterized the classes of frameworks distinguishable by the non-monotonic inference relation for the admissible semantics.

- *Joint work with R. Booth and L. van der Torre (Univ. of Luxembourg), published in FLAIRS 2013 [27]*

6.2.2. Dynamics in Abstract Argumentation

Recent years have seen a considerable work on dynamics in argumentation framework (AF). We addressed dynamics in abstract argumentation using a logical theory where an agent's belief state consists of an argumentation framework and a constraint that encodes the outcome the agent believes the argumentation framework should have. Dynamics enters in two ways: (1) the constraint is strengthened upon learning that the AF should have a certain outcome and (2) the argumentation framework is expanded upon learning about new arguments/attacks. A problem faced in this setting is that a constraint may be inconsistent with the AF's outcome. We discussed two ways to address this problem: First, it is still possible to form consistent fallback beliefs, i.e., beliefs that are most plausible given the agent's argumentation framework and constraint. Second, we showed that it is always possible to find argumentation framework expansions to restore consistency. Our work combines various individual approaches in the literature on argumentation dynamics in a general setting.

- *Joint work with R. Booth and L. van der Torre (Univ. of Luxembourg), published in SUM 2013. [26]*

Preferences have been intensively studied in argumentation framework. Preference-based argumentation frameworks are instantiation of Dung's framework in which the defeat relation (in the sense of Dung) is computed from an attack relation and a preference relation over the set of arguments. We distinguish between different ways to derive preferences over arguments, e.g., from their relative specificity, relative strength or from values promoted by the arguments. However an underexposed aspect in these models is change of preferences. We proposed a dynamic model of preferences in argumentation, centering on what we call property-based AFs. It is based on Dietrich and List's model of property-based preference and it provides an account of how and why preferences in argumentation may change. The idea is that preferences over arguments are derived from preferences over properties of arguments, and change as the result of moving to different motivational states. We also provided a dialogical proof theory that establishes whether there exists some motivational state in which an argument is accepted.

- *Joint work with R. Booth (Univ. of Luxembourg), published in ADT 2013.*

6.2.3. Representing Synergy Among Arguments with Choquet Integral

Preference-based argumentation frameworks are instantiation of Dung's framework in which the defeat relation (in the sense of Dung) is computed from an attack relation and a preference relation over the set of arguments. Value-based argumentation framework is a preference-based argumentation framework where the preference relation over arguments is derived from a preference relation over values they promote. We extended value-based argumentation framework with collective defeats and arguments promoting values with various strengths. In the extended framework, we defined a function which computes the strength of a collective defeat. We also defined desired properties for the proposed function. Surprisingly, we showed that this function obeying the corresponding properties is Choquet integral, a well-known aggregation function at work in multiple criteria decision.

- *Joint work with C. Labreuche (Thales), published in EC-SQARU 2013 [35]*

6.2.4. Compiling Preference Queries in Qualitative Constraint Problems

Comparative preference statements are the basic ingredients of conditional logics for representing users' preferences in a compact way. These statements may be strict or not and obey different semantics. Algorithms have been developed in the literature to compute a preference relation over outcomes given a set of comparative preference statements and one or several semantics. These algorithms are based on insights from non-monotonic reasoning (more specifically, minimal and maximal specificity principles) enforcing the preference

relations to be a complete preorder. The main limitation of these logics however relies in preference queries when comparing two outcomes. Indeed given two outcomes having the same preference w.r.t. the preference relation, there is no indication whether this equality results from an equality between two preference statements or the outcomes are in fact incomparable and equality has been enforced by specificity principles. On the other hand, comparative preference statements and their associated semantics can be translated into qualitative constraint satisfaction problems in which one can have a precise ordering over two outcomes. We investigated this bridge and provided a compilation of conditional logics-based preference queries in qualitative constraint problems.

- *Joint work with J.-F. Condotta (CRIL), published in FLAIRS 2013 [31]*

6.2.5. Argumentation for Reasoning with Inconsistencies

We investigate the use of argumentation when reasoning over an inconsistent knowledge base. We use argumentation in this context given the explanation power that it may bring (and that is currently under investigation).

We have investigated logical based argumentation following two methods. First, we have defined our own argument and attack notion (given the logical language at hand) and showed that such instantiation respects desirable properties of consistency and maximality (called rationality postulates in the field). This work has showed that the ICR, AR, IAR semantics investigated by inconsistent query answering (see Pagoda, Section 8.1) are the same as skeptically preferred or stable semantics, grounded and universally stable or preferred. Such result is encouraging as it bridges the two communities (argumentation and inconsistent query answering) allowing to use results from one field in order to enrich the other. We have also investigated the practical applicability of such argument definition and approach in the selection of flour for bread.

- *Joint work with Srdjan Vesic (Univ. of Luxembourg), published in RIA 2013 [23] and SUM 2013 [32]*

On the other hand we have also looked at using a generic logical argumentation framework (ASPIC) in order to instantiate it with a simple logic in the EcoBioCap project (see Section 8.2). We have extended previous results to enrich bipolar queries. A software tool is under construction.

- *Work published in RIA 2013 [21]*

6.3. Semantic Data Integration

Participants: Michel Chein, Madalina Croitoru, Léa Guizol, Michel Leclère.

It often happens that different references (i.e. data descriptions), possibly coming from heterogeneous data sources, concern the same real world entity. In such cases, it is necessary: (i) to detect whether different data descriptions really refer to the same real world entity and (ii) to fuse them into a unique representation. Since the seminal paper [59], this issue has been studied under various names: “record linking”, “entity resolution”, “reference resolution”, “de-duplication”, “object identification”, “data reconciliation”, etc., mostly in databases (cf. the bibliography by William E. Winckler [60]). It has become one of the major challenges in the Web of Data, where the objective is to link data published on the web and to process them as a single distributed database.

We investigate this problem in the specific context of bibliographic databases. Indeed, people working in bibliographical information systems have a lasting tradition of using norms and have integrated, along collections of documents notices (e.g. bibliographic records), collections of *authority notices* that categorize the different named entities used to describe documents (people, organizations, places, ...). In current databases, documents notices do not use directly the names of named entities to fill a particular field (author, editor, ...), but the unique identifier of the authority notice representing that named entity.

Past years, we began a collaboration with ABES (National Bibliographic Agency for Universities) to develop a method and a prototype to perform entity resolution between on one hand the authors of a new bibliographic record, and, on the other the authority references of an authority catalog (and namely the Sudoc catalogue from the ABES agency). The prototype providing this service has been implemented on top of Cogui and experiments have been led in the context of the SudocAd project (jointly conducted by ABES and GraphIK).

Our proposed method can be stated as follows: first, enrich authority records with knowledge extracted from bibliographic records in which the authority is mentioned ; then, use logical rules which conclude on different levels of reconciliation, to compare the authors of a new bibliographic record with the enriched authority records ; finally, for each author of the new bibliographic record, order the authority identifiers by level of reconciliation.

- *Work published in [30].*

A problem with this approach is that it relies upon pre-established links between bibliographic records and authority notices. However, our experimentation and evaluation have shown that many existing links were erroneous, and thus led to the propagation of new linkage errors. We have thus began to work on methods and tools to repair linkage errors in bibliographical databases. This year, this work has been pursued along three different axis:

1. We have built a formal framework allowing to evaluate the quality of links in a documents database. We propose two different “quality” notions, based upon an identification predicate *id* and a differentiation predicate *di* between pairs of authority notices identifiers (these predicates can be either given by an expert or computed using rules). We have first introduced the notion of a *well-founded* database, when *id* is an equivalence relation and *di* its complement. This property can be checked using logical inferences and combinatorial techniques. In the general case where a database is not necessarily well-founded, we have proposed different distances to a well-founded one. We have also introduced a more complex quality criterion that corresponds to *stability by substitution* (a fundamental property of logical equality that is not necessarily satisfied by *id*).
 - *A research report should lead to a publication in 2014.*
2. We developed a methodology for detecting linkage errors and fixing them, based upon a clustering method of authors in bibliographic records. Last year, the general schema of the methodology was defined. It is based upon a set of criteria which allows us to cluster “similar” authors together. Each criterion represents a point of view on the author: name, publication time span, publication domain, etc... This year, two aggregation semantics for such criteria have been developed, implemented and evaluated.
 - *Work published in AI-SGAI 2013 [34].*
3. We have studied methods allowing to automatically extract similarity criteria between named entities. This problem is very similar to the automatic discovery of composite key constraints in RDF data sources that conform to a given ontology. We have studied the different existing methods allowing to discover such keys, and have proposed logical semantics for these different keys. These semantics allow to understand and compare the results produced by these different methods. These methods have been evaluated against the documentary databases provided by our partners ABES and INA.
 - *Work described in a research report [48], at the moment, two papers are submitted.*

LAGADIC Project-Team

6. New Results

6.1. Visual tracking

6.1.1. 3D model-based tracking

Participants: Antoine Petit, Eric Marchand.

This study focused on the issue of estimating the complete 3D pose of the camera with respect to a potentially textureless object, through model-based tracking. We proposed to robustly combine complementary geometrical and color edge-based features in the minimization process, and to integrate a multiple-hypotheses framework in the geometrical edge-based registration phase [53], [52], [68], [11].

6.1.2. Pose estimation through multi-planes tracking

Participants: Bertrand Delabarre, Eric Marchand.

This study dealt with dense visual tracking robust towards scene perturbations using 3D information to provide a space-time coherency. The proposed method is based on a piecewise-planar scenes visual tracking algorithm which aims at minimizing an error between an observed image and reference templates by estimating the parameters of a rigid 3D transformation taking into account the relative positions of the planes in the scene. Both the sum of conditional variance and mutual information have been considered [40] [67].

6.1.3. Pose estimation from spherical moments

Participant: François Chaumette.

This study has been realized in collaboration with Omar Tahri from ISR in Coimbra (Portugal) and Youcef Mezouar from Institut Pascal in Clermont-Ferrand. It was devoted to the classical PnP (Perspective-from-N-Points) problem whose goal is to estimate the pose between a camera and a set of known points from the image measurement of these points. We have developed a new method based on invariant properties of the spherical projection model, allowing us to decouple the pose estimation in two steps: the first one provides the translation by minimizing a criterium using an iterative Newton-like method, the second one directly provides the rotation by solving a Procrustes problem [65], [26].

6.1.4. Structure from motion

Participants: Riccardo Spica, Paolo Robuffo Giordano, François Chaumette.

Structure from motion (SfM) is a classical and well-studied problem in computer and robot vision, and many solutions have been proposed to treat it as a recursive filtering/estimation task. However, the issue of *actively* optimizing the transient response of the SfM estimation error has not received a comparable attention. In the work [64], we studied the problem of designing an online active SfM scheme characterized by an error transient response equivalent to that of a reference linear second-order system with desired poles. Indeed, in a nonlinear context, the observability properties of the states under consideration are not (in general) time-invariant but may depend on the current state and on the current inputs applied to the system. It is then possible to simultaneously act on the estimation gains and system inputs (i.e., the camera velocity for SfM) in order to optimize the observation process and impose a desired transient response to the estimation error. The theory developed in [64] has a general validity and can be applied to many different contexts: in [64] it is shown how to tailor the proposed machinery to two concrete SfM problems involving structure estimation for point features and for planar regions from measured image moments.

6.1.5. 3D reconstruction of transparent objects

Participant: Patrick Rives.

This work has been realized in collaboration with Nicolas Alt, Ph.D. student at the “Technische Universität München” (TUM).

Visual geometry reconstruction of unstructured domestic or industrial scenes is an important problem for applications in virtual reality, 3D video or robotics. With the advent of Kinect sensor, accurate and fast methods for 3D reconstruction have been proposed. However, transparent objects cannot be reconstructed with methods that assume a consistent appearance of the observed 3D structure for different viewpoints. We proposed an algorithm that searches the depth map acquired by a depth camera for inconsistency effects caused by transparent objects. Consistent scene parts are filtered out. The result of our method hence complements existing approaches for 3D reconstruction of Lambertian objects [30].

6.1.6. *Pseudo-semantic segmentation*

Participants: Rafik Sekkal, Marie Babel.

This study has been realized in collaboration with Ferran Marques from Image Processing Group of the Technical University of Catalonia (Barcelona). We designed a video segmentation framework based on contour projections. This 2D+t technique provides a joint hierarchical and multiresolution solution. Results obtained on state-of-the-art benchmarks have demonstrated the ability of our framework to insure the spatio-temporal consistency of the regions along the sequence.

6.1.7. *Augmented reality*

Participants: Pierre Martin, Eric Marchand.

Using Simultaneous Localization And Mapping (SLAM) methods becomes more and more common in Augmented Reality (AR). To achieve real-time requirement and to cope with scale factor and the lack of absolute positioning issue, we proposed to decouple the localization and the mapping step. This approach has been validated on an Android Smartphone through a collaboration with Orange Labs [46].

Dealing with AR, we have proposed a method named Depth-Assisted Rectification of Patches (DARP), which exploits depth information available in RGB-D consumer devices to improve keypoint matching of perspective distorted images [44].

6.2. Visual servoing

6.2.1. *Photometric moment-based visual servoing*

Participants: Manikandan Bakthavatchalam, François Chaumette.

This goal of this work is to use a set of photometric moments as visual features for visual servoing. We first determined the analytical form of the interaction matrix related to these moments. From the results obtained in the past from binary moments, we then selected a set of four features to control four degrees of freedom (dof) with excellent decoupling and stability properties [35]. More recently, thanks to a collaboration with Omar Tahri from ISR Coimbra in Portugal, these results have been extended to the full six dof case.

6.2.2. *Visual servoing of humanoid robot*

Participant: François Chaumette.

This study has been realized in collaboration with the Pal robotics company located in Barcelona, Spain. It was devoted to the control of the arm of a humanoid robot by visual servoing for manipulation tasks [29].

6.2.3. *Visual servoing of cable-driven parallel robot*

Participant: François Chaumette.

This study is realized in collaboration with Rémy Ramadour and Jean-Pierre Merlet from Coprin group at Inria Sophia Antipolis. Its goal is to adapt visual servoing techniques for cable-driven parallel robot in order to achieve accurate manipulation tasks. This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6).

6.2.4. Nanomanipulation

Participants: Le Cui, Eric Marchand.

We began a work, within the ANR P2N Nanorobust project (see Section 8.2.1), on the development of micro- and nano-manipulation within SEM (Scanning Electron Microscope). Our goal is to provide visual servoing techniques for positioning and manipulation tasks with a nanometer precision. This year, we focused on the characterisation of the projection model of a SEM along with the approach required for its calibration.

6.3. Visual navigation of mobile robots

6.3.1. New RGB-D sensor design for indoor 3D mapping

Participants: Eduardo Fernandez Moral, Patrick Rives.

A multi-sensor device has been developed for omnidirectional RGB-D (color+depth) image acquisition (see Figure 5 .a). This device allows acquiring such omnidirectional images at high frame rate (30 Hz). This approach has advantages over other alternatives used nowadays in terms of accuracy and real-time spherical image construction of indoor environments, which are of particular interest for mobile robotics. This device has important prospective applications, such as fast 3D-reconstruction or simultaneous localization and mapping (SLAM). A novel calibration method for such device has been developed. It does not require any specific calibration pattern, taking into account the planar structure of the scene to cope with the fact that there is no overlapping between sensors. A method to perform image registration and visual odometry has also been developed. This method relies in the matching of planar primitives that can be efficiently obtained from the depth images. This technique performs considerably faster than previous registration approaches based on ICP.

6.3.2. Long term mapping

Participants: Tawsif Gokhool, Patrick Rives.

This work inscribes in the context of lifelong navigation and map building. The kind of representation that we focus on is made up of a topometric map consisting of a graph of spherical RGB-D views. Thanks to the use of a saliency map built from the photometric and geometric data, we are able to characterize the conditioning of the pose estimation algorithm and to keep as keyframes only a subset of the spherical RGB-D views acquired on the fly. Subsequently, a study on the spread of keyframes was made. The aim was to investigate ways of covering completely and optimally the explored environment in a pose graph representation. Again, over here, the benefits are twofold. Firstly, data acquisition at a throttle of 30 Hz induces many redundant information in the database, which may not necessarily contribute much to the registration phase. Therefore, intelligent selection of keyframes helped in the reduction of data redundancy. Furthermore, as pointed out in the literature, frame to keyframe alignment has the advantage of reducing trajectory drift since the propagation error is diminished as well (see Figure 5 .b)

6.3.3. Semantic mapping

Participants: Romain Drouilly, Patrick Rives.

Semantic mapping aims at building rich cognitive representations of the world in addition to classical topometric maps. A dense labeling has been achieved from high resolution outdoor images using an approach combining Random Forest (RF) and Conditional Random Field (CRF). A second development dealt with the use of semantic information for localization in indoor scenes. For this kind of scenes dense labeling is more difficult due to the large number of potential classes. Therefore algorithms developed for this task rely on a sparse representation of indoor environments called “pbmap”. It consists of a graph whose nodes are the planes present in a given scene. These planes are the only parts of the scene that are labeled. Very high labeling rates of planes has been reached (more than 90%) and it has been shown that these labeled planes could be useful for localization and navigation tasks.

6.3.4. Automous navigation of wheelchairs

Participants: Rafik Sekkal, François Pasteau, Marie Babel.

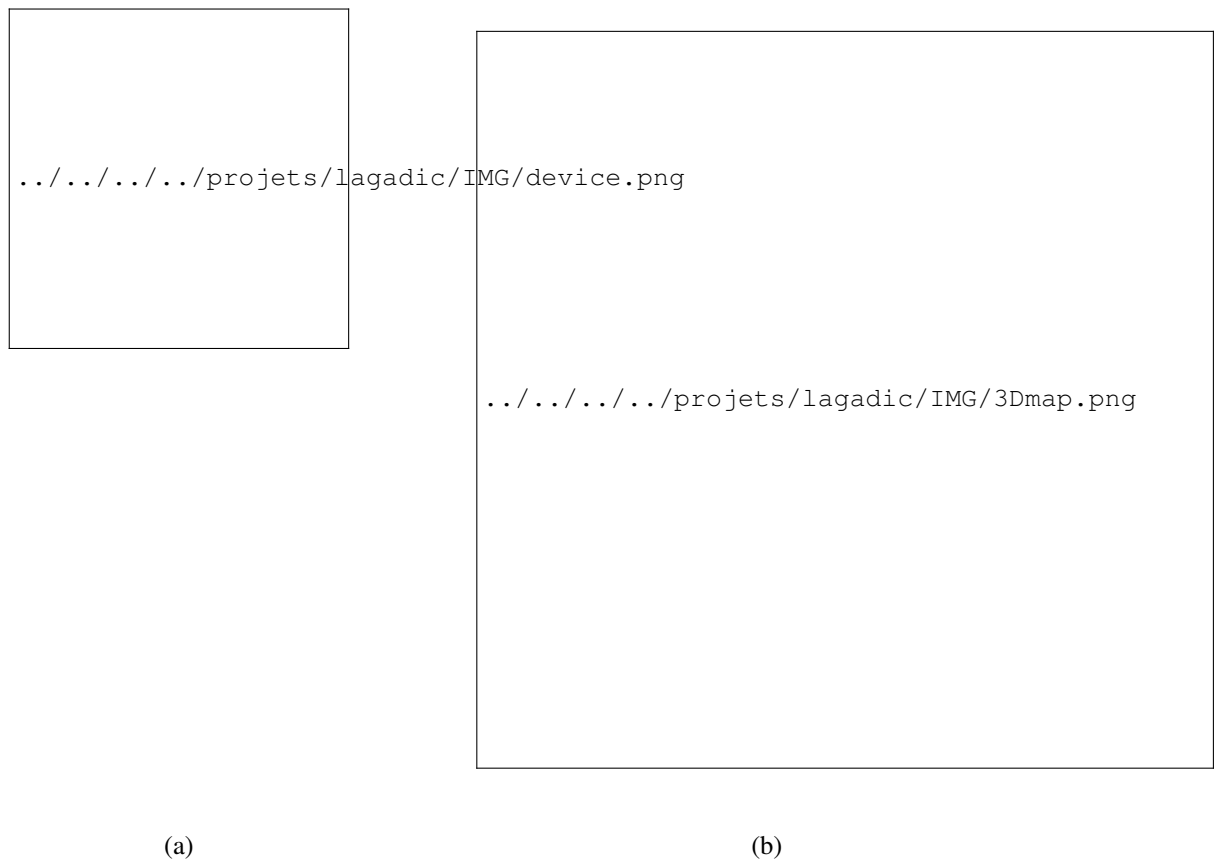


Figure 5. a) Omnidirectional RGB-D sensor, b) Top view of dense visual SLAM with fusion of intensity and depth

The goal of this work is to design an autonomous navigation framework of a wheelchair by means of a single camera and visual servoing. We focused on a corridor following task where no prior knowledge of the environment is required. The servoing process matches the non-holonomic constraints of the wheelchair and relies on two visual features, namely the vanishing point location and the orientation of the median line formed by the straight lines related to the bottom of the walls [60]. This overcomes the initialization issue typically raised in the literature. The control scheme has been implemented onto a robotized wheelchair and results show that it can follow a corridor with an accuracy of ± 3 cm [50]. This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6) as well as of the Apash project (see Section 8.1.2).

6.3.5. *Semi-autonomous control of a wheelchair for navigation assistance along corridors*

Participants: Marie Babel, François Pasteau, Alexandre Krupa.

This study concerns a semi-autonomous control approach that we designed for safe wheelchair navigation along corridors. The control relies on the combination of a primary task of wall avoidance performed by a dedicated visual servoing framework and a manual steering task. A smooth transition from manual driving to assisted navigation is obtained thanks to a gradual visual servoing activation method that guarantees the continuity of the control law. Experimental results clearly show the ability of the approach to provide an efficient solution for wall avoiding purposes. This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6) as well as of the Apash project (see Section 8.1.2).

6.3.6. *Target tracking*

Participants: Ivan Markovic, François Chaumette.

This study was realized in the scope of the FP7 Regpot Across project (see Section 8.3.1.2) during the three-month visit of Ivan Markovic, Ph.D. student at the University of Zagreb. It consisted in developing a pedestrian visual tracking from an omni-directional fish-eye camera and a visual servoing control scheme so that a mobile robot is able to follow the pedestrian. This study has been validated on our Pioneer robot (see Section 5.5).

6.3.7. *Obstacle avoidance*

Participants: Fabien Spindler, François Chaumette.

This study was realized in collaboration with Andrea Cherubini who is now Assistant Prof. at Université de Montpellier. It is concerned with our long term researches about visual navigation from a visual memory without any accurate 3D localization [9]. In order to deal with obstacle avoidance while preserving the visibility in the visual memory, we have proposed a control scheme based on tentacles for fusing the data provided by a pan-tilt camera and a laser range sensor [14]. Recent progresses have been obtained by considering moving obstacles [39].

6.4. Medical robotics

6.4.1. *Needle detection and tracking in 3D ultrasound*

Participants: Pierre Chatelain, Alexandre Krupa.

We developed an algorithm for detecting and tracking a flexible needle in a sequence of 3D ultrasound volumes when it is manually inserted, without any a priori information on the insertion direction. Our approach is based on the combination of a RANSAC algorithm with Kalman filtering in a closed loop fashion and allows real-time tracking of the needle. In addition, a pose-based visual servoing was developed for automatically moving a robotized 3D ultrasound probe in order to keep the needle tip centered in the volume and to align its main axis with the central plane of the volume. This needle detection algorithm and probe automatic guidance were experimentally validated during the insertion of a needle in a gelatin phantom [38].

6.4.2. *Non-rigid target tracking in ultrasound images*

Participants: Marie Babel, Alexandre Krupa.

In order to robustly track the motion of a tumour or cyst during needle insertion, we developed a new approach to track a deformable target within a sequence of 2D ultrasound images. It is based on a dedicated hierarchical grid interpolation algorithm (HGI) that is typically used for real-time video compression purposes. This approach provides a continuous motion representation of the target by using a grid of control points that models both their global displacement and local deformations. The motion of each control point is estimated by a hierarchical and multi-resolution local search method in order to minimize the sum of squared difference of the target pixel intensity between successive images. This new approach was validated from 2D ultrasound images of real human tissues undergoing rigid and non-rigid deformations.

6.4.3. Adaptive arc-based path planning for robot-assisted needle 3D steering using duty-cycling control technique

Participant: Alexandre Krupa.

This study concerned the development of a method for three dimensional steering of a beveled-tip flexible needle that can be used in medical robotics for percutaneous assistance procedures. The proposed solution is the extension of an adaptive arc-based 2D planar approach. It combines the Rapidly-Exploring Random Tree (RRT) algorithm, the duty-cycling needle control technique and stop and turn phases to reorientate the needle in a new working plane each time it is necessary. Simulation results demonstrate the feasibility of this approach to reach a 3D target while avoiding obstacles and its robustness to needle kinematic model errors.

6.4.4. Gait analysis

Participants: Cyril Joly, Patrick Rives.

Clinical evaluation of frailty in the elderly is the first step to decide the degree of assistance they require. Advances in robotics make it possible to turn a standard assistance device into an augmented device that may enrich the existing tests with new sets of daily measured criteria. We designed an augmented 4-wheeled rollator, equipped with a Kinect and odometers, for daily biomechanical gait analysis. It allows to estimate on line legs and feet configurations during the walk. Preliminary results [43] obtained on four healthy persons show that relevant data can be extracted for gait analysis (e.g. foot orientation and tibia-foot angle, feet position) during an assisted walk.

This work has been realized in collaboration with Claire Dune from the University of Toulon and in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6).

6.5. Control of single and multiple UAVs

6.5.1. State estimation and flight control of quadrotor UAVs

Participants: Riccardo Spica, Paolo Robuffo Giordano.

Over the last years the robotics community witnessed an increasing interest in the Unmanned Aerial Vehicle (UAV) field. In particular quadrotor UAVs have become more and more widespread in the community as experimental platform for, e.g., testing novel 3D planning, control and estimation schemes in real-world indoor and outdoor conditions. Indeed, in addition to being able to take-off and land vertically, quadrotors can reach high angular accelerations thanks to the relatively long lever arm between opposing motors. This makes them more agile than most standard helicopters or similar rotorcraft UAVs, and thus very suitable to realize complex tasks such as aerial mapping, air pollution monitoring, traffic management, inspection of damaged buildings and dangerous sites, as well as agricultural applications such as pesticide spraying.

Key components for the successful deployment of such systems are (i) a reliable state estimation module able to deal with highly unstructured and/or GPS-denied indoor environments, and (ii) a robust flight control algorithm able to cope with model uncertainties and external disturbances (e.g., adverse atmospheric conditions). The difficulty of these estimation and control problems is also increased by the limited amount of sensing and processing capabilities onboard standard quadrotors: this clearly imposes additional strict requirements on the complexity of the employed algorithms.

In the context of robust flight control of standard quadrotors, the works [31], [32] addressed the theoretical developments and experimental validation of a novel nonlinear adaptive flight controller able to estimate online the UAV dynamic parameters (such as the position of the center of mass when carrying unmodeled payloads), and to compensate for external wind gusts. In parallel, we also developed in [63] a high performance and open-source hardware/software control architecture for flight control of quadrotor UAVs made available to the general public on a open repository. This was achieved by combining state-of-the-art filtering and control techniques with a careful customization and calibration of a commercially available and low-cost quadrotor platform. Finally, still in the context of flight control, the work [58] reported a successful experimental validation of several flight tests for a novel overactuated quadrotor design with tilting propellers behaving as a fully-actuated rigid body in 3D space (thus, able to control its position and orientation in a fully decoupled way).

As for state estimation, the work [41] introduces a novel nonlinear estimation filter meant to obtain a metric measurement of the body-frame linear velocity from optical flow decomposition (thus, visual input) and concurrent fusion of the accelerometer/gyro readings from the onboard IMU. The peculiarity of this filtering technique is the possibility to both explicitly characterize and impose the transient response of the estimation error (thus, the filter performance) by acting on the estimation gains and UAV motion (acceleration). This is in contrast with the consolidated use of EKF schemes which, because of their inherent linearization of the system dynamics, do not typically allow to draw any conclusions about the stability/transient response of the estimation error.

These works were realized in collaboration with the robotics groups at the University of Cassino, Italy, and at the Max Planck Institute for Biological Cybernetics, Tübingen, Germany.

6.5.2. Collective control of multiple UAVs

Participant: Paolo Robuffo Giordano.

The challenge of coordinating the actions of multiple robots is inspired by the idea that proper coordination of many simple robots can lead to the fulfilment of arbitrarily complex tasks in a robust (to single robot failures) and highly flexible way. Teams of multi-robots can take advantage of their number to perform, for example, complex manipulation and assembly tasks, or to obtain rich spatial awareness by suitably distributing themselves in the environment. Within the scope of robotics, autonomous search and rescue, firefighting, exploration and intervention in dangerous or inaccessible areas are the most promising applications.

In the context of multi-robot (and multi-UAV) coordinated control, *connectivity* of the underlying graph is perhaps the most fundamental requirement in order to allow a group of robots accomplishing common goals by means of *decentralized* solutions. In fact, graph connectivity ensures the needed continuity in the data flow among all the robots in the group which, over time, makes it possible to share and distribute the needed information. In this respect, in [23] a fully decentralized strategy for continuous connectivity maintenance for a group of UAVs has been theoretically developed and experimentally validated on a team of 4 quadrotor UAVs. An extension for allowing an external planner (e.g., a human user) to vary online the minimum degree of connectivity of the group was also proposed in [59]. Finally, [48] dealt with the issue of coupling the purely reactive strategy for connectivity maintenance with an autonomous exploration algorithm in a cluttered 3D environment (still experimentally tested on a team of quadrotor UAVs). The complete software architecture developed for performing these and similar multi-UAV experiments was also published in [42].

These works were realized in collaboration with the robotics group at the Max Planck Institute for Biological Cybernetics, Tübingen, Germany.

REVES Project-Team

5. New Results

5.1. Plausible and Realistic Image Rendering

5.1.1. Depth Synthesis and Local Warps for Interactive Image-based Navigation

Participants: Gaurav Chaurasia, Sylvain Duchene, George Drettakis.



Figure 3. Novel views generated by the image-based rendering approach of [12] along with a visualization of novel camera position relative to the 3D scene and input cameras. This approach is among the first to handle very complex urban scenes such as those shown here and provide a stable solution for viewpoints that are far from the input cameras.

Modern camera calibration and multi-view stereo techniques enable users to smoothly navigate between different views of a scene captured using standard cameras. The underlying automatic 3D reconstruction methods work well for buildings and regular structures but often fail on vegetation, vehicles and other complex geometry present in everyday urban scenes. Consequently, missing depth information makes image-based rendering for such scenes very challenging. This paper introduces a new image-based rendering algorithm that is robust to missing or unreliable geometry, providing plausible novel views even in regions quite far

from the input camera positions. The approach first oversegments the input images, creating superpixels of homogeneous color content which preserve depth discontinuities. It then introduces a *depth synthesis* step for poorly reconstructed regions. It defines a graph on the superpixels and uses *shortest walk* traversals to fill unreconstructed regions with approximate depth from regions that are well-reconstructed and similar in visual content. The superpixels augmented with synthesized depth allow a local shape-preserving warp which warps each superpixel of the input image to the novel view without incurring distortions and preserving the local visual content within the superpixel. This allows the approach to effectively compensate for missing photoconsistent depth, the lack of which is known to cause rendering artifacts. The final rendering algorithm blends the warped images, using heuristics to avoid ghosting artifacts. The results demonstrate novel view synthesis in real time for multiple challenging scenes with significant depth complexity (see Figure 3), providing a convincing immersive navigation experience. The paper presents comparisons with three of the state of the art image-based rendering techniques and demonstrate clear advantages.

This work was in collaboration with Olga Sorkine-Hornung at ETH Zurich. It has been published in ACM Transactions on Graphics 2013 [12] and presented at SIGGRAPH.

5.1.2. *Megastereo: Constructing High-Resolution Stereo Panoramas*

Participant: Christian Richardt.

There is currently a strong consumer interest in a more immersive experience of content, such as 3D photographs, television and cinema. A great way of capturing environmental content are panoramas (see Figure 4). We present a solution for generating high-quality stereo panoramas at megapixel resolutions. While previous approaches introduced the basic principles, we show that those techniques do not generalise well to today's high image resolutions and lead to disturbing visual artefacts. We describe the necessary correction steps and a compact representation for the input images in order to achieve a highly accurate approximation to the required ray space. In addition, we introduce a flow-based upsampling of the available input rays which effectively resolves known aliasing issues like stitching artefacts. The required rays are generated on the fly to perfectly match the desired output resolution, even for small numbers of input images. This upsampling is real-time and enables direct interactive control over the desired stereoscopic depth effect. In combination, our contributions allow the generation of stereoscopic panoramas at high output resolutions that are virtually free of artefacts such as seams, stereo discontinuities, vertical parallax and other mono-/stereoscopic shape distortions.

This work was carried out in collaboration with Yael Pritch, Henning Zimmer and Alexander Sorkine-Hornung at Disney Research Zurich. The paper has been published as an oral presentation at CVPR 2013 [20].

5.1.3. *Probabilistic Connection Path Tracing*

Participants: Stefan Popov, George Drettakis.

We propose an unbiased generalization of bi-directional path tracing (BPT) that significantly improves its rendering efficiency. Our main insight is that the set of paths traced by BPT contains a significant amount of statistical information, that is not exploited.

BPT repeatedly builds an eye and a light sub-paths, connects them, estimates the contribution to the corresponding pixel and then throws the path away. Instead, we propose to first trace all eye and light sub-paths, and then probabilistically connect each eye sub-path to one or more light sub-paths. From a Monte-Carlo perspective, this will connect each light to each eye sub-path, substantially increasing the number of paths used to estimate the solution. As a result, the convergence will be significantly increased as well.

This work is a collaboration with Frédo Durand from the Massachusetts Institute of Technology, Cambridge and Ravi Ramamoorthi from University of California, Berkeley in the context of the CRISP Associated Team.

5.1.4. *Parallelization Strategies for Associative Image Processing Operators*

Participants: Gaurav Chaurasia, George Drettakis.



Figure 4. A stereoscopic panorama corrected and stitched using our techniques, shown as red-cyan anaglyph image.

Basic image processing operations have been optimized on a case-by-case basis such as prefix sums and recursive filters. Moreover, these optimized algorithms are very complicated to program because parallelization involves non-trivial splitting of the input domain of the operator. The target of this is to generalize the optimization heuristics of a generic class of associative image processing operators by developing an algebraic understanding of the operator and parallelization options. The algebra can transform associative operations such as box filters, summed area table, recursive filters etc. by splitting their domain to smaller subsets of the input image that can be executed in parallel and recombine the intermediate result later. The ultimate target is to develop a compiler front-end based on the Halide language that implements this algebra and is capable of parallelizing associative operators of arbitrary footprints by a few lines of code, thereby relieving the programmer of the tedious task for programming the parallelized algorithms. Such a compiler would allow programmers to easily experiment with a plethora of parallelization strategies in a systematic manner.

This work is in collaboration with Jonathan Ragan-Kelley and Fredo Durand of MIT and Sylvain Paris (Adobe Research).

5.1.5. *Lightfield Editing*

Participant: Adrien Bousseau.

Lightfields capture multiple nearby views of a scene and are consolidating themselves as the successors of conventional photographs. As the field grows and evolves, the need for tools to process and manipulate lightfields arises. However, traditional image manipulation software such as Adobe Photoshop are designed to handle single views and their interfaces cannot cope with multiple views coherently. In this work we evaluate different user interface designs for lightfield editing. Our interfaces differ mainly in the way depth is presented to the user and build upon different depth perception cues.

This work is a collaboration with Adrian Jarabo, Belen Masia and Diego Gutierrez from Universidad de Zaragoza and Fabio Pellacini from Sapienza Universita di Roma.

5.2. Perception for Plausible Rendering

5.2.1. *Perception of Perspective Distortions in Image-Based Rendering*

Participants: Peter Vangorp, Christian Richardt, Gaurav Chaurasia, George Drettakis.

Image-based rendering (IBR) creates realistic images by enriching simple geometries with photographs, for example by mapping the photograph of a building façade onto a plane. However, as soon as the viewer moves away from the correct viewpoint, the image in the retina becomes distorted, sometimes leading to gross misperceptions of the original geometry. Two hypotheses from vision science state how viewers perceive such image distortions, one claiming that they can compensate for them (and therefore perceive scene geometry reasonably correctly), and one claiming that they cannot compensate (and therefore can perceive rather significant distortions). We modified the latter hypothesis so that it extends to street-level IBR. We then conducted a rigorous experiment that measured the magnitude of perceptual distortions that occur with IBR for façade viewing. We also conducted a rating experiment that assessed the acceptability of the distortions. The results of the two experiments were consistent with one another. They showed that viewers' percepts are indeed distorted, but not as severely as predicted by the modified vision science hypothesis. From our experimental results, we develop a predictive model of distortion for street-level IBR, which we use to provide guidelines for acceptability of virtual views and for capture camera density. We perform a confirmatory study to validate our predictions, and illustrate their use with an application that guides users in IBR navigation to stay in regions where virtual views yield acceptable perceptual distortions (see Figure 5).

This work is a collaboration with Emily Cooper and Marty Banks at UC Berkeley, within the associate team CRISP. The paper was accepted as a SIGGRAPH 2013 paper and published in the ACM Transactions on Graphics journal [18].

5.2.2. *Gloss Perception in Painterly and Cartoon Rendering*

Participant: Adrien Bousseau.



Figure 5. This interactive navigation tool shows an inset (in the lower left) that predicts comfort ratings for all possible camera orientations as seen from the blue camera's viewpoint. The application also restricts the user's motion to regions with acceptable predicted quality (in blue and yellow).

Depictions with traditional media such as painting and drawing represent scene content in a stylized manner. It is unclear however how well stylized images depict scene properties like shape, material and lighting. In this project, we use non photorealistic rendering algorithms to evaluate how stylization alters the perception of gloss (see Figure 6). Our study reveals a compression of the range of representable gloss in stylized images so that shiny materials appear more diffuse in painterly rendering, while diffuse materials appear shinier in cartoon images.

From our measurements we estimate the function that maps realistic gloss parameters to their perception in a stylized rendering. This mapping allows users of NPR algorithms to predict the perception of gloss in their images. The inverse of this function exaggerates gloss properties to make the contrast between materials in a stylized image more faithful. We have conducted our experiment both in a lab and on a crowdsourcing website. While crowdsourcing allows us to quickly design our pilot study, a lab experiment provides more control on how subjects perform the task. We provide a detailed comparison of the results obtained with the two approaches and discuss their advantages and drawbacks for studies similar to ours.



Figure 6. The experimental task used for studying gloss perception in stylized images.

This work is a collaboration with James O'Shea, Ravi Ramamoorthi and Maneesh Agrawala from UC Berkeley in the context of the Associate Team CRISP (see also Section 1) and Frédo Durand from MIT. It has been published in ACM Transactions on Graphics 2013 [11] and presented at SIGGRAPH.

5.2.3. A High-Level Visual Attention Model

Participant: George Drettakis.

The goal of this project is to develop a high-level attention model based on memory schemas and singleton theory in visual perception. We have developed an approach extending a Bayesian approach to attention, which incorporates these high level features and can be directly used in a game engine to improve scene design.

This project is in collaboration with the Tech. University of Crete in the context of the Ph.D. of George Koulieris, supervised by Prof. Katerina Mania and BTU Cottburg (D. Cunningham).

5.3. Interaction and Design for Virtual Environments

5.3.1. Diffusion Curves: A Vector Representation for Smooth-Shaded Images

Participant: Adrien Bousseau.

This paper was selected for presentation in the Communications of the ACM, as an important graphics research result of interest to the entire Computer Science community. We describe a new vector-based primitive for creating smooth-shaded images, called the diffusion curve. A diffusion curve partitions the space through which it is drawn, defining different colors on either side. These colors may vary smoothly along the curve. In addition, the sharpness of the color transition from one side of the curve to the other can be controlled. Given a set of diffusion curves, the final image is constructed by solving a Poisson equation whose constraints are specified by the set of gradients across all diffusion curves (Figure 7). Like all vector-based primitives, diffusion curves conveniently support a variety of operations, including geometry-based editing, keyframe animation, and ready stylization. Moreover, their representation is compact and inherently resolution independent. We describe a GPU-based implementation for rendering images defined by a set of diffusion curves in real time. We then demonstrate an interactive drawing system allowing artists to create artwork using diffusion curves, either by drawing the curves in a freehand style, or by tracing existing imagery. Furthermore, we describe a completely automatic conversion process for taking an image and turning it into a set of diffusion curves that closely approximate the original image content.

This work is a collaboration with Alexandrina Orzan, Pascal Barla (Inria / Manao), Holger Winnemöller (Adobe Systems), Joëlle Thollot (Inria / Maverick) and David Salesin (Adobe Systems). This work was originally published in ACM Transactions on Graphics (Proceeding of SIGGRAPH 2008) and was selected for publication in Communications of the ACM July 2013 [15].

5.3.2. Natural Gesture-based Interaction for Complex Tasks in an Immersive Cube

Participants: Emmanuelle Chapoulie, George Drettakis.

We present a solution for natural gesture interaction in an immersive cube in which users can manipulate objects with fingers of both hands in a close-to-natural manner for moderately complex, general purpose tasks. Our solution uses finger tracking coupled with a real-time physics engine, combined with a comprehensive approach for hand gestures, which is robust to tracker noise and simulation instabilities. To determine if our natural gestures are a feasible interface in an immersive cube, we perform an exploratory study for tasks involving the user walking in the cube while performing complex manipulations such as balancing objects. We compare gestures to a traditional 6-DOF Wand, and we also compare both gestures and Wand with the same task, faithfully reproduced in the real world. Users are also asked to perform a free task, allowing us to observe their perceived level of presence in the scene. Our results show that our robust approach provides a feasible natural gesture interface for immersive cube-like environments and is perceived by users as being closer to the real experience compared to the Wand.



Figure 7. A diffusion curve consists of a Bézier curve (a) enriched with color (b) and blur (c) control points. The final image (d) is obtained by diffusing the colors in the image domain.

This work is a collaboration with Jean-Christophe Lombardo of SED, with Evanthia Dimara and Maria Roussou from the University of Athens and with Maud Marchal from IRISA-INSA/Inria Rennes - Bretagne Atlantique. The work is under review in the journal Virtual Reality.

5.3.3. *Evaluation of Direct Manipulation in an Immersive Cube: a Controlled Study*

Participants: Emmanuelle Chapoulie, George Drettakis.

We are pursuing a study for interaction using finger tracking and traditional 6 degrees of freedom (DOF) flysticks in a virtual reality immersive cube. Our study aims at identifying which factors make one interface better than the other and which are the tradeoffs for the design of experiments, thus decomposing the movements into restricted DOF.

5.3.4. *The Drawing Assistant: Automated Drawing Guidance and Feedback from Photographs*

Participants: Emmanuel Iarussi, Adrien Bousseau.

Drawing is the earliest form of visual depiction and continues to enjoy great popularity with paint systems. However, drawing requires artistic skills that many people feel out of reach. We developed an interactive drawing tool that provides automated guidance over model photographs to help people practice traditional drawing-by-observation techniques. The drawing literature describes a number of techniques to help people gain consciousness of the shapes in a scene and their relationships. We compile these techniques and derive a set of construction lines that we automatically extract from a model photograph (see Figure 8). We then display these lines over the model to guide its manual reproduction by the user on the drawing canvas. Our pen-based interface also allows users to navigate between the techniques they wish to practice and to draw construction lines in dedicated layers. We use shape-matching to register the user's sketch with the model guides. We use this registration to provide corrective feedback to the user. We conducted two user studies to inform the design of our tool and evaluate our approach with a total of 20 users. Participants produced better drawings using the drawing assistant, with more accurate proportions and alignments. They also perceived that guidance and corrective feedback helped them better understand how to draw. Finally, some participants spontaneously applied the techniques when asked to draw without our tool after using it for about 30 minutes.

This work is a collaboration with Theophanis Tsandilas from the InSitu project team - Inria Saclay, in the context of the ANR DRAO project. It has been published at proceedings of UIST 2013 the 26th annual ACM symposium on User interface software and technology [19].

5.3.5. *Shape-Aware Sketch Editing with Covariant-Minimizing Cross Fields*

Participants: Emmanuel Iarussi, Adrien Bousseau.

Free-hand sketches are extensively used in product design for their ability to convey 3D surfaces with a handful of pen strokes. Skillful artists capture all surface information by strategically positioning strokes so that they depict the feature lines and curvature directions of surface patches. Viewers envision the intended 3D surface by mentally interpolating these lines to form a dense network representative of the curvature of the shape. Our goal is to mimic this interpolation process to estimate at each pixel of a sketch the projection of the two principal directions of the surface, or their extrapolation over umbilic regions. While the information we recover is purely 2D, it provides a vivid sense of the intended 3D surface and allows various shape-aware sketch editing applications, including normal estimation for shading, cross-hatching rendering and surface parameterization for texture mapping.

This work is a collaboration with David Bommès from the Titane project team, Sophia-Antipolis.

5.3.6. *Depicting Stylized Materials with Vector Shade Trees*

Participants: Jorge Lopez-Moreno, Stefan Popov, Adrien Bousseau, George Drettakis.



Figure 8. Our drawing assistant provides guidance and feedback over a model photograph that the user reproduces on a virtual canvas (a). We use computer vision algorithms to extract visual guides that enhance the geometric structures in the image (b). In this example, the user first sketched the block-in construction lines (c, blue) before drawing the regions and adding details. This guidance helps users produce more accurate drawings.



Figure 9. Depicting Stylized Materials with Vector Shade Trees.

Vector graphics represent images with compact, editable and scalable primitives. Skillful vector artists employ these primitives to produce vivid depictions of material appearance and lighting. However, such stylized imagery often requires building complex multi-layered combinations of colored fills and gradient meshes. We facilitate this task by introducing vector shade trees that bring to vector graphics the flexibility of modular shading representations as known in the 3D rendering community. In contrast to traditional shade trees that combine pixel and vertex shaders, our shade nodes encapsulate the creation and blending of vector primitives that vector artists routinely use. We propose a set of basic shade nodes that we design to respect the traditional guidelines on material depiction described in drawing books and tutorials. We integrate our representation as an Adobe Illustrator plug-in that allows even inexperienced users to take a line drawing, apply a few clicks and obtain a fully colored illustration. More experienced artists can easily refine the illustration, adding more details and visual features, while using all the vector drawing tools they are already familiar with. We demonstrate the power of our representation by quickly generating illustrations of complex objects and materials.

Figure 9 illustrates how our algorithm works. We use a combination of basic shade nodes composed of vector graphics primitives to describe Vector Shade Trees that represent stylized materials (a). Combining these nodes allows the depiction of a variety of materials while preserving traditional vector drawing style and practice. We integrate our vector shade trees in a vector drawing tool that allows users to apply stylized shading effects on vector line drawings (b,c).

This work is a collaboration with Maneesh Agrawala from University of California, Berkeley in the context of the CRISP Associated Team. The work was accepted as a SIGGRAPH 2013 paper and published in ACM Transactions on Graphics, volume 32, issue 4 [14].

5.3.7. Auditory-Visual Aversive Stimuli Modulate the Conscious Experience of Fear

Participants: Rachid Guerchouche, George Drettakis.

In a natural environment, affective information is perceived via multiple senses, mostly audition and vision. However, the impact of multisensory information on affect remains relatively undiscovered. In this study, we investigated whether the auditory-visual presentation of aversive stimuli influences the experience of fear. We used the advantages of virtual reality to manipulate multisensory presentation and to display potentially fearful dog stimuli embedded in a natural context. We manipulated the affective reactions evoked by the dog stimuli by recruiting two groups of participants: dog-fearful and non-fearful participants. The sensitivity to dog fear was assessed psychometrically by a questionnaire and also at behavioral and subjective levels using a Behavioral Avoidance Test (BAT). Participants navigated in virtual environments, in which they encountered virtual dog stimuli presented through the auditory channel, the visual channel or both. They were asked to report their fear using Subjective Units of Distress. We compared the fear for unimodal (visual or auditory) and bimodal (auditory-visual) dog stimuli. Dog-fearful participants as well as non-fearful participants reported more fear in response to bimodal audiovisual compared to unimodal presentation of dog stimuli. These results suggest that fear is more intense when the affective information is processed via multiple sensory pathways, which might be due to a cross-modal potentiation. Our findings have implications for the field of virtual reality-based therapy of phobias. Therapies could be refined and improved by implicating and manipulating the multisensory presentation of the feared situations.

This work is a collaboration with Marine Taffou and Isabelle Viaud-Delmon from CNRS-IRCAM, in the context of the European project VERVE. The work was published in the Multisensory Research journal 2013 [17].

5.3.8. Memory Motivation Virtual Experience

Participants: Emmanuelle Chapoulie, Rachid Guerchouche, George Drettakis.

Memory complaints are known to be one the first stages of Alzheimer's disease, for which -up to now, there is no known chemical treatment. In the context of the European project VERVE, and in collaboration with the Resources and Research Memory Centre of Nice Hospital (CM2R), we performed a study on the feasibility of treating memory complaints using realistic immersive virtual environments. Such environments are created



Figure 10. Pictures of the auditory-visual VEs used to measure the participants' fear when encountering virtual dogs. On the left, the outdoor garden scene and on the right, the indoor hangar scene.

using Image-Based Rendering technique developed by REVES. It is possible to easily provide, realistic 3D environments of places familiar to the participants using only a few photograph, and investigate whether IBR virtual environments can convey familiarity.

This work is a collaboration with Pierre-David Petit and Pr. Philippe Robert from CM2R. The work will be presented in IEEE Virtual Reality conference 2014 and will be published in the conference proceedings.

5.3.9. Layered Image Vectorization

Participants: Christian Richardt, Adrien Bousseau, George Drettakis.

Vector graphics enjoy great popularity among graphic designers for their compactness, scalability and editability. The goal of *vectorization* algorithms is to facilitate the creation of vector graphics by converting bitmap images into vector primitives. However, while a vectorization algorithm should faithfully reproduce the appearance of a bitmap image, it should also generate vector primitives that are easily editable – a goal that existing methods have largely overlooked. We investigate layered representations which are more compact and editable, and hence better preserve the strengths of vector graphics. This work is in collaboration with Maneesh Agrawala in the context of the CRISP Associated Team and Jorge Lopez-Moreno, now a postdoc at the University of Madrid.

5.3.10. True2Form: Automatic 3D Concept Modeling from Design Sketches

Participants: Adrien Bousseau.

We developed a method to estimate smooth 3D shapes from design sketches. We do this by hypothesizing and perceptually validating a set of local geometric relationships between the curves in sketches. We then algorithmically reconstruct 3D curves from a single sketch by detecting their local geometric relationships and reconciling them globally across the 3D curve network.

This work is a collaboration with James McCrae and Karan Singh from the University of Toronto and Xu Baoxuan, Will Chang and Alla Sheffer from the University of British Columbia.

STARS Project-Team

6. New Results

6.1. Introduction

This year Stars has proposed new algorithms related to its three main research axes : perception for activity recognition, semantic activity recognition and software engineering for activity recognition.

6.1.1. Perception for Activity Recognition

Participants: Julien Badie, Slawomir Bak, Vasanth Bathrinarayanan, Piotr Bilinski, François Brémond, Guillaume Charpiat, Duc Phu Chau, Etienne Corvée, Carolina Garate, Vaibhav Katiyar, Ratnesh Kumar, Srinidhi Mukanahallipatna, Marco San Biago, Silviu Serban, Malik Souded, Kartick Subramanian, Anh Tuan Nghiem, Monique Thonnat, Sofia Zaidenberg.

This year Stars has extended an algorithm for tuning automatically the parameters of the people tracking algorithm. We have evaluated the algorithm for re-identification of people through a camera network while taking into account a large variety of potential features together with practical constraints. We have designed several original algorithms for the recognition of short actions and validated its performance on several benchmarking databases (e.g. ADL). We have also worked on video segmentation and representation, with different approaches and applications.

More precisely, the new results for perception for activity recognition concern:

- Background Subtraction and People Detection in Videos (6.2)
- Tracking and Video Representation (6.3)
- Video segmentation with shape constraint (6.4)
- Articulating motion (6.5)
- Lossless image compression (6.6)
- People detection using RGB-D cameras (6.7)
- Online Tracking Parameter Adaptation based on Evaluation (6.8)
- People Detection, Tracking and Re-identification Through a Video Camera Network (6.9)
- People Retrieval in a Network of Cameras (6.10)
- Global Tracker : an Online Evaluation Framework to Improve Tracking Quality (6.11)
- Human Action Recognition in Videos (6.12)
- 3D Trajectories for Action Recognition Using Depth Sensors (6.13)
- Unsupervised Sudden Group Movement Discovery for Video Surveillance (6.14)
- Group Behavior Understanding (6.15)

6.1.2. Semantic Activity Recognition

Participants: Guillaume Charpiat, Serhan Cosar, Carlos -Fernando Crispim Junior, Hervé Falciani, Baptiste Fosty, Qiao Ma, Rim Romdhane.

During this period, we have thoroughly evaluated the generic event recognition algorithm using both sensors (RGB and RGBD video cameras). This algorithm has been tested on more than 70 videos of older adults performing 15 min of physical exercises and cognitive tasks. In Paris subway, we have been able to demonstrate the recognition in live of group behaviours. We have also been able to store the meta-data (e.g. people trajectories) generated from the processing of 8 video cameras, each of them lasting 2 or 3 days. From these meta-data, we have automatically discovered few hundreds of rare events, such as loitering, collapsing, ... to display on the screen of subway security operators.

Concerning semantic activity recognition, the contributions are :

- Evaluation of an Activity Monitoring System for Older People Using Fixed Cameras (6.16)
- A Framework for Activity Detection of Older People Using Multiple Sensors (6.17)
- Walking Speed Detection on a Treadmill using an RGB-D Camera (6.18)
- Serious Game for older adults with dementia (6.19)
- Unsupervised Activity Learning and Recognition (6.20)
- Extracting Statistical Information from Videos with Data Mining (6.21)

6.1.3. Software Engineering for Activity Recognition

Participants: François Brémond, Daniel Gaffé, Julien Gueytat, Sabine Moisan, Anh Tuan Nghiem, Annie Ressouche, Jean-Paul Rigault, Luis-Emiliano Sanchez.

This year Stars has continued the development of the SUP platform. This latter is the backbone of the team experiments to implement the new algorithms. We continue to improve our meta-modelling approach to support the development of video surveillance applications based on SUP. This year we have focused on metrics to drive dynamic architecture changes and on component management. We continue the development of a scenario analysis module (SAM) relying on formal methods to support activity recognition in SUP platform. We improve the CLEM toolkit and we rely on it to build SAM. Finally, we are improving the way we perform adaptation in the definition of a multiple services for device adaptive platform for scenario recognition.

The contributions for this research axis are:

- SUP (6.22)
- Model-Driven Engineering for Activity Recognition (6.23)
- Scenario Analysis Module (6.24)
- The Clem Workflow (6.25)
- Multiple Services for Device Adaptive Platform for Scenario Recognition (6.26)

6.2. Background Subtraction and People Detection in Videos

Participants: Vasanth Bathrinathan, Srinidhi Mukanahallipatna, Silviu Serban, François Brémond.

Keywords: Background Subtraction, People detection, Automatic parameter selection for algorithm

Background Subtraction Background subtraction is a vital real time low-level algorithm, which differentiates foreground and background objects in a video. We have thoroughly evaluated our Extended Gaussian Mixture model containing a shadows-removal algorithm, which performs better than other state of the art methods. Figure 10 shows the comparison of 13 background subtraction algorithms results on a challenging railway station monitoring video dataset from Project CENTAUR, which includes illumination change, shadows, occlusion and moving trains. Our algorithms performs the best in terms of result and with good processing speed too. Figure 11 is an example of our background subtraction algorithm's output on an indoor sequence of a surveillance footage from the Project SUPPORT.

Ongoing research include automatic parameter selection for this algorithm based on some learnt context. Since tuning the parameters is a daunting task for a non-experienced person, we try to learn some context information in a video like occlusion, contrast variation, density of foreground, texture etc. and map them to appropriate parameters of segmentation algorithm. Thus designing a controller to automatically adapt parameters of a algorithm as the scene context changes over time.

People Detection

A new robust real-time person detection system was proposed [45], which aims to serve as solid foundation for developing solutions at an elevated level of reliability. Our belief is that clever handling of input data correlated with efficacious training algorithms are key for obtaining top performance. A comprehensive training method on very large training database and based on random sampling that compiles optimal classifiers with minimal bias and overfit rate is used. Building upon recent advances in multi-scale feature computations, our approach attains state-of-the-art accuracy while running at high frame rate.



Figure 10. Background Subtraction result on confidential dataset from CENTAUR project

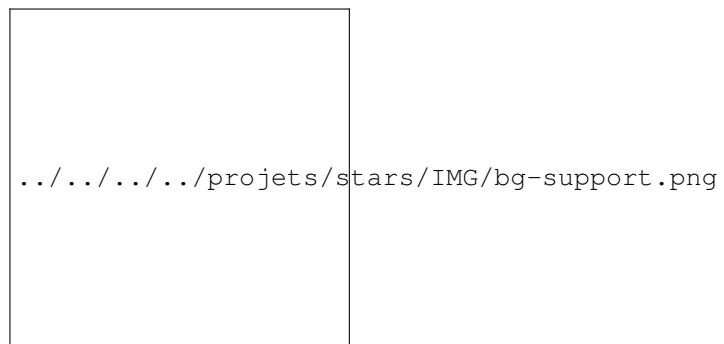


Figure 11. Background Subtraction result on a video to count number of people walking through the door after using their badge inside the terminal area (Project SUPPORT) - Autonomous Monitoring for Securing European Ports

Our method combines detection techniques that greatly reduce computational time without compromising accuracy. We use efficient LBP and MCT features which we compute on integral images for optimal retrieval of rectangular region intensity and nominal scaling error. AdaBoost is used to create cascading classifiers with significantly reduced detection time. We further refine detection speed by using the soft cascades approach and by transferring all important computation from the detection stage to the training stage. Figure 12 shows some output samples from various datasets which it was tested on.



Figure 12. Detection output from PETS (left-top), VANAHEIM (right-top), Hospital (left-bottom) and ETISEO (right-bottom)

6.3. Tracking and Video Representation

Participants: Ratnesh Kumar, Guillaume Charpiat, Monique Thonnat.

keywords: Fibers, Graph Partitioning, Message Passing, Iterative Conditional Modes, Video Segmentation, Video Inpainting

Multiple Object Tracking The objective is to find trajectories of objects (belonging to a particular category) in a video. To find possible occupancy locations, an object detector is applied to all frames of a video, yielding bounding boxes. Detectors are not perfect and may provide false detections; they may also miss objects sometimes. We build a graph of all detections, and aim at partitioning the graph into object trajectories. Edges in the graph encode factors between detections, based on the following :

- Number of common point tracks between bounding boxes (the tracks are obtained from an optical-flow-based point tracker)
- Global appearance similarity (based on the pixel colors inside the bounding boxes)
- Trajectory straightness : for three bounding boxes at different frames, we compute the Laplacian (centered at the middle frame) of the centroids of the boxes.
- Repulsive constraint : Two detections in a same frame cannot belong to the same trajectory.

We compute the partitions by using sequential tree re-weighted message passing (TRW-S). To avoid local minima, we use a label flipper motivated from the Iterative Conditional Modes algorithm.

We apply our approach to typical surveillance videos where object of interest are humans. Comparative quantitative results can be seen in Tables 1 and 2 for two videos. The evaluation metrics considered are : Recall, Precision, Average False Alarms Per Frame (FAF), Number of Groundtruth Trajectories (GT), Number of Mostly Tracked Trajectories, Number of Fragments (Frag), Number of Identity Switches (IDS), Multiple Object Tracking Accuracy (MOTA) and Multiple Object Tracking Precision (MOTP).

This work has been submitted to CVPR' 14.

Table 1. Towncenter Video Output

Method	MOTA	MOTP	Detector
[59] (450-750)	56.8	79.6	HOG
Ours (450-750)	53.5	69.1	HOG

Table 2. Comparison with recent proposed approaches on PETS S2L1 Video

Method	Recall	Precision	FAF	GT	MT	Frag	IDS
[77]	96.9	94.1	0.36	19	18	15	22
Ours	95.4	93.4	0.28	19	18	42	13

Video Representation We continued our work from the previous year on Fiber-Based Video Representation. During this year we focused on obtaining competitive results with the state-of-the-art (Figure 13).

The usefulness of our novel representation is demonstrated by a simple video inpainting task. Here a user input of only 7 clicks is required to remove the dancing girl disturbing the news reporter (Figure 14).

This work has been accepted for publication next year [41].

6.4. Video segmentation with shape constraint

Participant: Guillaume Charpiat.

keywords: video segmentation, graph-cut, shape growth, shape statistics, shape prior, dynamic time warping

6.4.1. Video segmentation with growth constraint

This is joint work with Yuliya Tarabalka (Ayin Inria team) and Björn Menze (ETH Zurich, also MIT and collaborator of Asclepios Inria team).



Figure 13. **Top Row:** Left image displays a sequence as a volumetric display. Right image displays all fibers found, clustered at a particular hierarchy. **Bottom Row :** Left Image displays the highest level of the hierarchical clustering, with fiber extension. Right Image shows the result obtained from [71]. **Our result demonstrates better long term temporal coherency.**



Figure 14. Inpainting task. **Left** : Original video (top) and xt slice (bottom) showing trajectories. **Right** : Our result. Clusters of fibers were computed and selected with only 7 mouse clicks to distinguish the disturbing girl from the reporter and background. The girl was removed and the hole was filled by extending the background fibers in time.

Context : One of the important challenges in computer vision is the automatic segmentation of objects in videos. This task becomes more difficult when image sequences are subject to low signal-to-noise ratio or low contrast between intensities of neighboring structures in the image scene. Such challenging data is acquired routinely, for example in medical imaging or in satellite remote sensing. While individual frames could be analyzed independently, temporal coherence in image sequences provides crucial information to make the problem easier. In this work, we focus on segmenting shapes in image sequences which only grow or shrink in time, and on making use of this knowledge as a constraint to help the segmentation process.

Approach and applications : We had proposed last year an approach based on graph-cut (see Figure 15), able to obtain efficiently (linear time in the number of pixels in practice), for any given video, its globally-optimal segmentation satisfying the growth constraint. This year we applied this method to three different applications :

- forest fires in satellite images,
- organ development in medical imaging (brain tumor, in multimodal MRI 3D volumes),
- sea ice melting in satellite observation, with a shrinking constraint instead of growth (see Figure 16).

The results on the first application were published in IGARSS (International Geoscience and Remote Sensing Symposium) [48], while the last two applications and the theory were published in BMCV [47]. A journal paper is also currently under review. A science popularization article was also published [53]. Not related but also with the Ayin Inria team was published the last of a series of articles about optimizers for point process models [40], introducing graph-cuts in the multiple birth and death approach in order to detect numerous objects that should not overlap.

6.4.2. Video segmentation with statistical shape prior

This is joint work with Maximiliano Suster (leader of the Neural Circuits and Behaviour Group at Bergen University, Norway).



Figure 15. The approach : segmenting all frames together with a single graph-cut, with growth or shrinkage constraint, instead of segmenting independently each frame.



Figure 16. Example of a noisy, challenging sequence of melting sea ice, from satellite observations (first column). The frames were aligned beforehand, using inside/outside histograms of pixel intensities. The following columns show the results of varied approaches, ranging from frame-by-frame segmentation to techniques ensuring shape smoothness in time. Our approach (last column) has the right suitable prior (shape shrinkage) and thus performs the best.

Context : The zebrafish larva is a model organism widely used in biology to study genetics. Therefore, analyzing its behavior in video sequences is particularly important for this research field. For this, there is a need to segment the animal in the video, in order to estimate its speed, and also more precisely to extract its shape, in order to express for instance how much it is bent, how fast it bends, etc. However, as the animal is stimulated by the experimenter with a probe, the full zebrafish larva is not always visible because of occlusion.

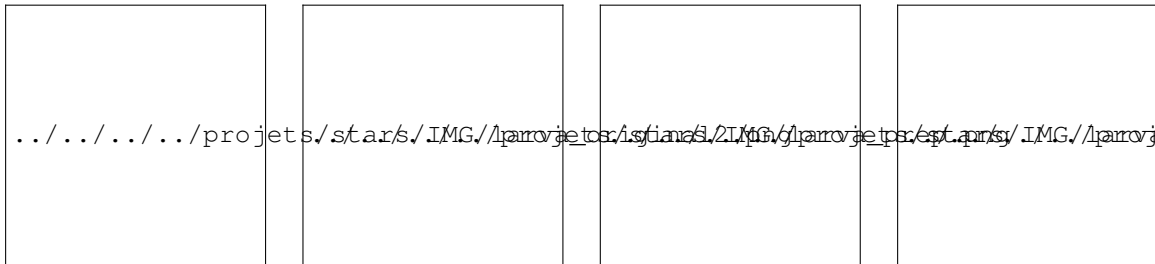


Figure 17. Example of a segmentation : initial image, processed image (based on video coherency), initialization of the active contour evolution, result. The total time spent per frame on average is reasonable for practical applications (magnitude order of 1 second).

Approach : We build a shape prior based on a training set of examples of non-occluded shapes, and use it to segment new images where the animal is occluded. This is however not straightforward.

- **Building a training set of shape deformations :** Given a set of training images containing non-occluded animals, we extract their contours via multiple robust thresholdings and morphomathematical operations. For each contour, we then estimate automatically the location of the tip of the tail. We then compute point-to-point correspondences between all contours, using a modified version of Dynamic Time Warping, as well as the approximate tip location information. This is done in a translation- and rotation-invariant way.
- **Building the shape prior :** Based on these matchings, the mean shape is computed, as well as modes of deformation with PCA.
- **Segmenting occluded images :** Images with occluded shapes are pre-processed in a similar way to non-occluded ones; however, the resulted segmentation does not contain only the parts of the larva but also the probe, which has potentially similar colors and location, and is moving. To identify the probe, whose shape depends on the video sequence, we make use of its rigidity and of temporal coherency. Then a segmentation criterion is designed to push an active contour towards the zones of interest (in a way that is robust to initialization), while keeping a shape which is feasible according to the shape prior.

Examples of data and results for a preliminary algorithm are shown in Figure 17 , with the associated shape prior shown in Figure 18 .

6.5. Articulating motion

Participant: Guillaume Charpiat.

keywords: shape evolution, metrics, gradient descent, Finsler gradient, Banach space, piecewise-rigidity, piecewise-similarity

This is joint work with Giacomo Nardi, Gabriel Peyré and François-Xavier Vialard (Ceremade, Paris-Dauphine University).



Figure 18. First deformation modes of the shape prior used in the segmentation above.

Context in optimization : A fact which is often ignored when optimizing a criterion with a gradient descent is that the gradient of a quantity depends on the metric chosen. In many domains, people choose by default the underlying L^2 metric, while it is not always relevant. Here we extend the set of metrics that can be considered, by building gradients for metrics that do not derive from inner products, with examples of metrics involving the L^1 norm, possibly of a derivative.

Mathematical foundations : This work introduces a novel steepest descent flow in Banach spaces. This extends previous works on generalized gradient descent, notably the work of Charpiat et al. [6], to the setting of Finsler metrics. Such a generalized gradient allows one to take into account a prior on deformations (e.g., piecewise rigid) in order to favor some specific evolutions. We define a Finsler gradient descent method to minimize a functional defined on a Banach space and we prove a convergence theorem for such a method. In particular, we show that the use of non-Hilbertian norms on Banach spaces is useful to study non-convex optimization problems where the geometry of the space might play a crucial role to avoid poor local minima.

Application to shape evolution : We performed some applications to the curve matching problem. In particular, we characterized piecewise-rigid deformations on the space of curves and we studied several models to perform piecewise-rigid evolutions (see Figure 19). We also studied piecewise-similar evolutions. Piecewise-rigidity intuitively corresponds to articulated motions, while piecewise-similarity further allows the elastic stretching of each articulated part independently. One practical consequence of our work is that any deformation to be applied to a shape can be easily and optimally transformed into an articulated deformation with few articulations, the number and location of the articulations being not known in advance. Surprisingly, this problem is actually convex.



Figure 19. Example of use of the Finsler gradient for the piecewise-rigid evolution of curves. Given an initial shape S and a target shape T , as well as a shape dissimilarity measure $E(S) = \text{Dissim}(S, T)$, any classical gradient descent on $E(S)$ would draw the evolving shape S towards the target T . However the metric considered to compute the gradient changes the path followed. The top row is the evolution obtained with a Sobolev gradient H^1 , which has the property of smoothing spatially the flow along the curve, to avoid irregular deformations. This is however not sufficient. The bottom row makes use of the Finsler gradient instead, with a metric favoring piecewise-rigid deformations.

An article was submitted to the journal *Interfaces and Free Boundaries* [52].

6.6. Lossless image compression

Participant: Guillaume Charpiat.

keywords: image compression, entropy coding, graph-cut

This is joint work with Yann Ollivier and Jamal Atif from the TAO Inria team.

Context : Understanding, modelling, predicting and compressing images are tightly linked, in that any good predictor can be turned into a good compressor via entropy coding (such as Huffman coding or arithmetic coding). Indeed, with such techniques, the more predictable an event E is, i.e. the higher its probability $p(E)$, the easier to compress it will be, with coding cost $-\log(p(E))$. Therefore we are interested in image compression, in order to build better models of images.

MDL approach : The state-of-the-art sequential prediction of time series based on the advice of various experts combines the different expert predictions, with weights depending on their individual past performance (cf. Gilles Stoltz and Peter Grünwald's work). This approach originates from the Minimum Description Length principle (MDL). This work was however designed for 1D data such as time series, and is not directly applicable to 2D data such as images. Consequently, our aim has been to adapt such an approach to the case of image compression, where time series are replaced with 2D series of pixel colors, and where experts are predictors of the color of a pixel given the colors of neighbors.

New method and results : This year, we have focused on lossless greyscale image compression, and proposed to encode any image with two maps, one storing the choice of the expert made for each pixel, and one storing the encoding of the intensity of each pixel according to its expert. In order to compress efficiently the first map, we ask the choices of experts to be coherent in space, and then encode the boundaries of the experts' areas. To find a suitable expert map, we optimize the total encoding cost explicitly, set as an energy minimization problem, solved with graph-cuts. An example of expert map obtained is shown in Figure 20. Preliminary results with a hierarchical ordering scheme already compete with standard techniques in lossless compression (PNG, lossless JPEG2000, JPEG-LS).

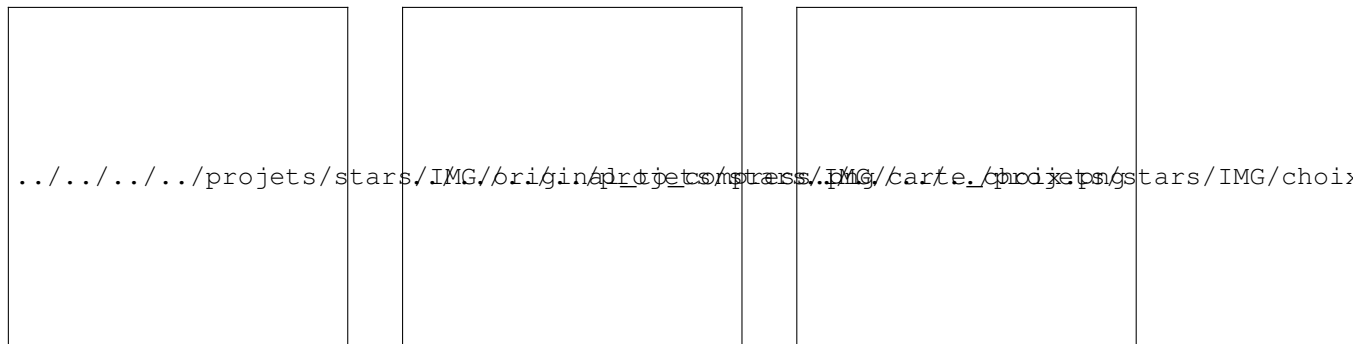


Figure 20. An image to encode; the map of the best experts, chosen independently for each pixel [each expert is represented by one color]; the expert map obtained with our approach enforcing spatial coherence in the expert choice.

6.7. People detection using RGB-D cameras

Participants: Anh-Tuan Nghiem, François Brémont.

keywords: people detection, HOG, RGB-D cameras

With the introduction of low cost RGB-D cameras like Kinect of Microsoft, video monitoring systems have another option for indoor monitoring beside conventional RGB cameras. Comparing with conventional RGB camera, reliable depth information from RGB-D cameras makes people detection easier. Besides that, constructors of RGB-D cameras also provide various libraries for people detection, skeleton detection or hand detection etc. However, perhaps due to high variance of depth measurement when objects are too far from the camera, these libraries only work when people are in the range of 0.5 to around 4.5 m from the cameras. Therefore, for our own video monitoring system, we construct our own people detection framework consisting of a background subtraction, a people classifier, a tracker and a noise removal component as illustrated in figure 21 .

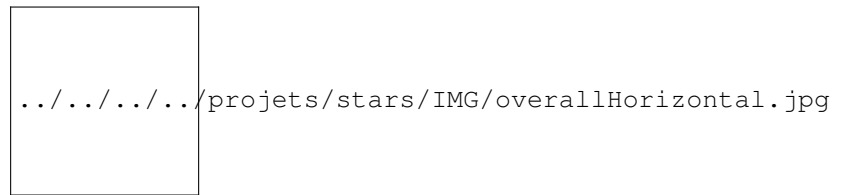


Figure 21. The people detection framework

In this system, the background subtraction algorithm is designed specifically for depth data. Particularly, the algorithm employs temporal filters to detect noise related to imperfect depth measurement on some special surface.

The people classification part is the extension of the work in [79]. From the foreground region provided by the background subtraction algorithm, the classification first searches for people head and then extracts HOG like features (Histogram of Oriented Gradient on binary image) above the head and the shoulder. Finally, these features are classified by a SVM classifier to recognise people.

The tracker links detected foreground regions in the current frame with the ones from previous frames. By linking objects in different frames, the tracker provides useful history information to remove noise as well as to improve the sensitivity of the people classifier.

Finally, the noise removal algorithm uses the object history constructed by the tracker to remove two types of noise: noise detected by temporal filter at the background subtraction algorithm and noise from high variance of depth measurement on objects far from the camera. Figure 22 illustrates the performance of noise removal on the detection results.

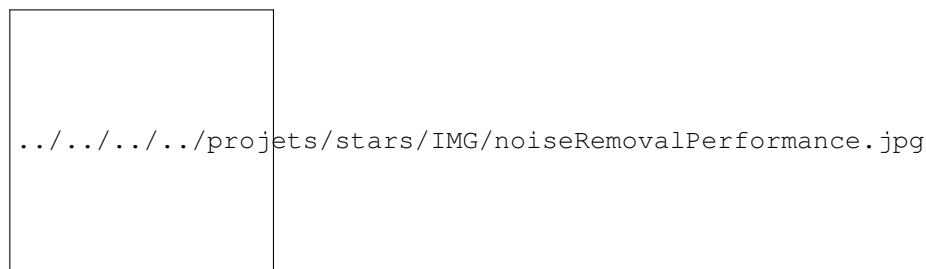


Figure 22. The people detection framework

The overall performance of our people detection framework is comparable to the one provided by Primesense, the constructor of RGB-D camera Microsoft Kinect.

Currently, we are doing extensive evaluation of the framework and the results will be submitted to a conference in the near future.

6.8. Online Tracking Parameter Adaptation based on Evaluation

Participants: Duc Phu Chau, Julien Badie, Kartick Subramanian, François Brémond, Monique Thonnat.

Keywords: Object tracking, parameter tuning, online evaluation, machine learning

Several studies have been proposed for tracking mobile objects in videos [50]. For example we have proposed recently a new tracker which is based on co-inertia analysis (COIA) of object features [44]. However the parameter tuning is still a common issue for many trackers. In order to solve this problem, we propose an online parameter tuning process to adapt a tracking algorithm to various scene contexts. The proposed approach brings two contributions: (1) an online tracking evaluation, and (2) a method to adapt online tracking parameters to scene contexts.

In an offline training phase, this approach learns how to tune the tracker parameters to cope with different contexts. Different learning schemes (e.g. neural network-based) are proposed. A context database is created at the end of this phase to support the control process of the considered tracking algorithm. This database contains satisfactory parameter values of this tracker for various contexts.

In the online control phase, once the tracking quality is evaluated as not good enough, the proposed approach computes the current context and tunes the tracking parameters using the learned values.

The experimental results show that the proposed approach improves the performance of the tracking algorithm and outperforms recent state of the art trackers. Figure 23 shows the correct tracking results of four people while occlusions happen. Table 3 presents the tracking results of the proposed approach and of some recent trackers from the state of the art. The proposed controller increases significantly the performance of an appearance-based tracker [63]. We obtain the best *MT* value (i.e. mostly tracked trajectories) compared to state of the art trackers.

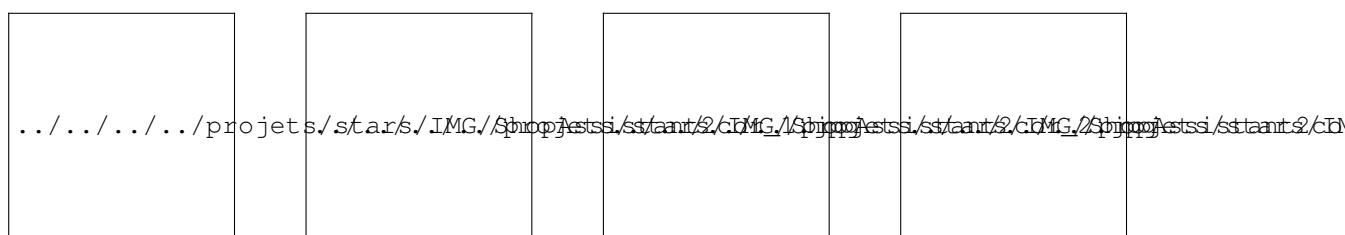


Figure 23. Tracking results of four people in the sequence *ShopAssistant2cor* (Caviar dataset) are correct, even when occlusions happen.

This work has been published in [33], [34].

6.9. People Detection, Tracking and Re-identification Through a Video Camera Network

Participants: Malik Souded, François Brémond.

keywords: People detection, Object tracking, People re-identification, Region covariance descriptors, SIFT descriptor, LogitBoost, Particle filters.

Table 3. Tracking results for the Caviar dataset. The proposed controller improves significantly the tracking performance. MT: Mostly tracked trajectories, higher is better. PT: Partially tracked trajectories. ML: Most lost trajectories, lower is better. The best values are printed in bold.

Approaches	MT (%)	PT (%)	ML (%)
Xing et al. [92]	84.3	12.1	3.6
Li et al. [76]	84.6	14.0	1.4
Kuo et al. [74]	84.6	14.7	0.7
D.P Chau et al. [63] without the proposed approach	78.3	16.0	5.7
D.P Chau et al. [63] with the proposed approach	85.5	9.2	5.3

This work aims at proposing a whole framework for people detection, tracking and re-identification through camera networks. Three main constraints have guided this work: high performances, real-time processing and genericity of the proposed methods (minimal human interaction/parametrization). This work is divided into three separate but dependent tasks:

6.9.1. People detection:

The proposed approach optimizes state-of-the-art methods [89], [93] which are based on training cascades of classifiers using the LogitBoost algorithm on region covariance descriptors. The optimization consists in clustering negative data before the training step, and speeds up both the training and detection processes while improving the detection performance. This approach has been published this year in [46]. The evaluation results and examples of detection are shown in Figures 24 and 25.

6.9.2. Object tracking:

The proposed object tracker uses a state-of-the-art background subtraction algorithm to initialize objects to track, with a collaboration of the proposed people detector in the case of people tracking. The object modelling is performed using SIFT features, detected and selected in a particular manner. The tracking process is performed at two levels: SIFT features are tracked using a specific particle filter, then object tracking is deduced from the tracked SIFT features using the proposed data association framework. A fast occlusion management is also proposed to achieve the object tracking process. The evaluation results are shown in Figure 26.

6.9.3. People re-identification:

A state-of-the-art method for people re-identification [67] is used as a baseline and its performance has been improved. A fast method for image alignment for multiple-shot case is proposed first. Then, texture information is added to the computed visual signatures. A method for people visible side classification is also proposed. Camera calibration information is used to filter candidate people who do not match spatio-temporal constraints. Finally, an adaptive feature weighting method according to visible side classification concludes the improvement contributions. The evaluation results are shown in Figure 27.

This work has been published in [28].

6.10. People Retrieval in a Network of Cameras

Participants: Sławomir Bąk, Marco San Biago, Ratnesh Kumar, Vasanth Bathrinarayanan, François Brémond.

keywords: Brownian statistics, re-identification, retrieval

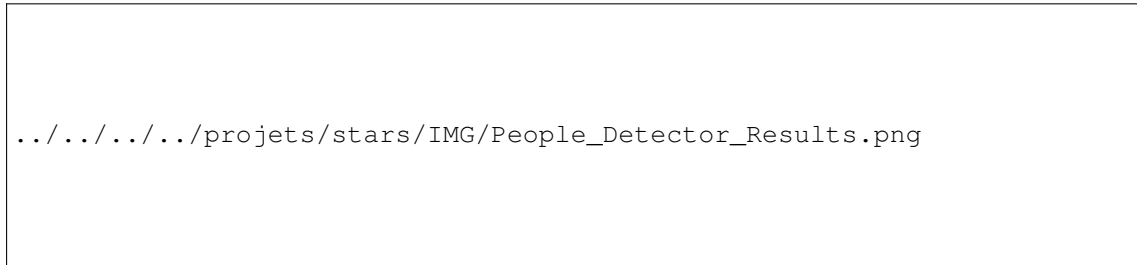


Figure 24. People detector evaluation and comparison on Inria, DaimlerChrysler, Caltech and CAVIAR datasets.

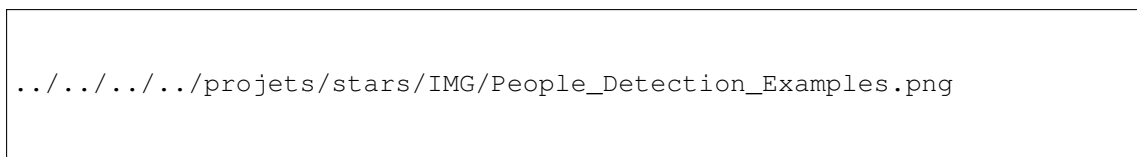


Figure 25. Some examples of detection using the proposed people detector.

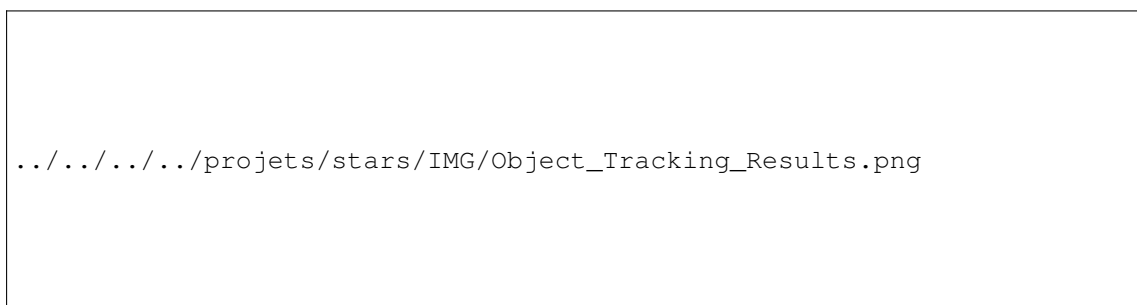


Figure 26. Object tracking evaluation on: (a) CAVIAR dataset using MT, PT and ML metrics. (b) ETI-VS1-BE-18-C4 sequence from ETISEO dataset, using ETISEO metrics.

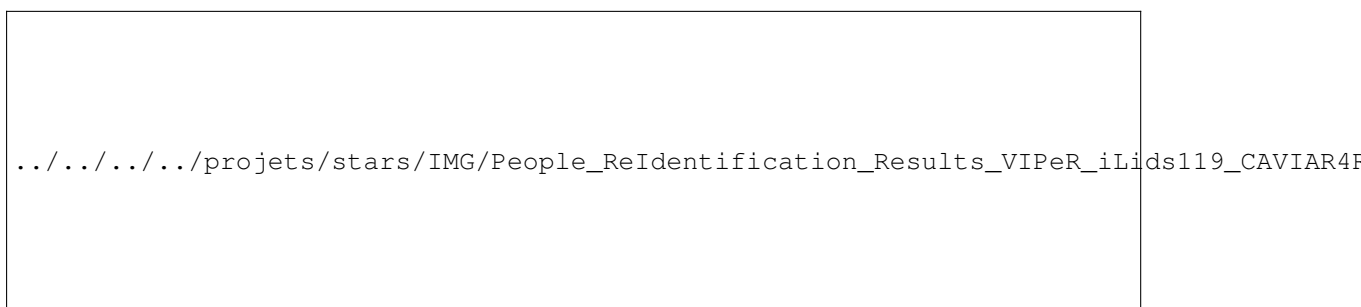


Figure 27. People re-identification evaluation on VIPeR (left), iLids-119 (middle) and CAVIAR4REID (right) datasets.

Task. Person re-identification (also known as multi-camera tracking) is defined as the process of determining whether a given individual has already appeared over a network of cameras. In most video surveillance scenarios, features such as face or iris are not available due to video low-resolution. Therefore a robust modeling of the global appearance of an individual (clothing) is necessary for re-identification. This problem is particularly hard due to significant appearance changes caused by variations in view angle, lighting conditions and different person pose. In this year, we focused on the two following aspects: new image descriptors and a design of a retrieval tool.

New image region descriptors. We have evaluated different image descriptors *w.r.t.* their recognition accuracy. As the covariance descriptor achieved the best results, we have employed this descriptor using different learning strategies to achieve the most accurate model for representing a human appearance [51]. We have also proposed a new descriptor based on recent advances in mathematical statistics related to Brownian motion [31]. This new descriptor outperforms the classical covariance in terms of matching accuracy and efficiency. We show that the proposed descriptor can capture richer characteristics than covariance, especially when fusing nonlinearly dependent features, which is often the case for images. The effectiveness of the approach is validated on three challenging vision tasks: object tracking & person re-identification [31] and pedestrian classification (the paper submitted to conference CVPR 2014). In all our experiments, we demonstrate competitive results while in person re-identification and tracking we significantly outperform the state-of-the-art.

New design of retrieval tool for a large network of cameras. Owing to the complexity of the re-identification problem, current state of the art approaches have relatively low retrieval accuracy, thus a fully automated system is still unattainable. However, we propose a retrieval tool [30], [29] that helps a human operator to solve the re-identification task (see Figure 28). This tool allows a human operator to browse images of people extracted from a network of cameras: to detect a person on one camera and to re-detect the same person few minutes later on another camera. The main stream is displayed on the left of the screen, while retrieval results are shown on the right. The results show lists of the most similar signatures extracted from each camera (green boxes indicate the correctly retrieved person). Below the main stream window a topology of the camera network is displayed. Detection and single camera tracking (see the main stream) are fully automatic. The human operator only needs to select a person of interest, thus producing retrieval results (right screen). The operator can easily see a preview of the retrieval results and can go directly to the original video content.

Perspectives. Currently, we are working not only on invariant image descriptors, which provide high recognition accuracy, but also on improving the alignment of the person pose, while matching appearance from cameras with significant difference in viewpoint. In addition to re-identification technology, we also work on designing an intuitive graphical interface, an important tool for the human operator analyzing retrieval results. Displaying retrieval results from a large camera network is still an issue, even after applying time-space constraints (the usage of topology of cameras).



(a)

Figure 28. Re-identification tool

Acknowledgements

This work has been supported by PANORAMA and CENTAUR European projects.

6.11. Global Tracker : an Online Evaluation Framework to Improve Tracking Quality

Participants: Julien Badie, Slawomir Bak, Duc Phu Chau, François Brémond, Monique Thonnat.

keywords: online quality estimation, improving tracking results

This work addresses the problem of estimating the quality of a tracking algorithm during runtime and correcting the anomalies found. Evaluating and tuning a tracking algorithm generally requires multiple runs and a ground truth. The proposed online evaluation framework, called global tracker, overcome these limitations by proposing a three-steps algorithm to improve tracking results in any kind of situations (mono-camera, camera network, 3D camera, ...).

The first step aims at correcting small tracking errors (when detections in consecutive frames are missing from an object trajectory) by interpolating the detected object data.

The second steps aims at detecting and correcting any anomaly found in the output of the tracking algorithm. For each detected object on each frame, we compute three different sets of features : the features that are computed using only data from the object (eg. appearance, size, ...), the features that measure the level of interaction between two objects (eg. occlusion level, density) and the features that measure the level of interaction between the object and the environment (eg. occlusion with background element, entering or leaving zones, ...). By studying the evolution of the coefficients of variation of each feature, some anomalies can be detected. Then, by minimizing an energy function based on the object-only features, we correct the output of the tracking algorithm.

The final step uses re-acquisition and re-identification methods to merge detected objects representing the same real object. This algorithm aims at correcting ID change errors when an object leaves the scene and reappears in another camera or when the object reappears after a long-term occlusion. The method used here is a constrained clustering algorithm that create groups of detections representing the same real object.

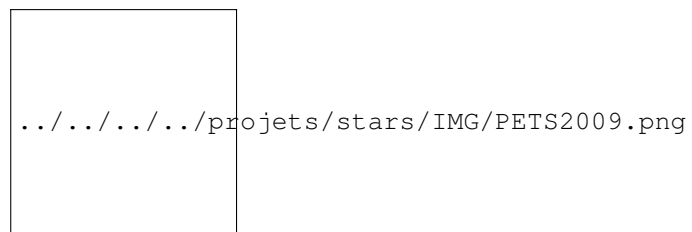


Figure 29. An example of the global tracker goal : offline learning of occlusion zones to manage online occlusion risks and optimize object trajectory.

This approach has been tested on several datasets (PETS 2009, Caviar, TUD-Stadtmitte). The results show that the global tracker, even associated with a tracking algorithm that does not have good results, can perform nearly as well as the state of the art and even exactly as well when a good tracker is used. On the Caviar dataset, the global tracker is even able to slightly outperform the result of the state of the art.

A part of this approach is described in an article published in AVSS 2013 [33]. This article shows how a tracking algorithm can use the global tracker results to tune its parameters and improve its results. This work was also used to improve the tracking results in 2 papers [38] [54].

Table 4. Comparison of the tracking results using CLEAR metrics on the sequence S2.L1 of the PETS 2009 dataset with and without the global tracker

Method	MOTA	MOTP	\bar{M}
Berclaz et al. [60]	0.80	0.58	0.69
Shitrit et al. [58]	0.81	0.58	0.70
Henriques et al. [72]	0.85	0.69	0.77
Chau et al. [33] without global tracker	0.62	0.63	0.63
Chau et al. [33] with global tracker	0.85	0.71	0.78

6.12. Human Action Recognition in Videos

Participants: Piotr Bilinski, Etienne Corvée, Slawomir Bak, François Brémond.

keywords: action recognition, tracklets, head detection, relative tracklets, bag-of-words.

In this work we address the problem of recognizing human actions in video sequences for home care applications.

Recent studies have shown that approaches which use a bag-of-words representation reach high action recognition accuracy. Unfortunately, these approaches have problems to discriminate similar actions, ignoring spatial information of features.

We propose a feature representation for action recognition based on dense point tracklets, head position estimation, and a dynamic coordinate system. Our main idea is that action recognition ought to be performed using a dynamic coordinate system corresponding to an object of interest. Therefore, we introduce a relative tracklet descriptor based on relative positions of a tracklet according to the central point of our dynamic coordinate system. As a center of our dynamic coordinate system, we choose the head position, providing description invariant to camera viewpoint changes. We use the bag-of-words approach to represent a video sequence and we capture global distribution of tracklets and relative tracklet descriptors over a video sequence. The proposed descriptors introduce spatial information to the bag-of-words model and help to distinguish similar features detected at different positions (*e.g.* to distinguish similar features appearing on hands and feet). Then we apply the Support Vector Machines with exponential chi-squared kernel to classify videos and recognize actions.

We report experimental results on three action recognition datasets (publicly available KTH and ADL datasets, and our locally collected dataset). Our locally collected dataset has been created in cooperation with the CHU Nice Hospital. It contains people performing daily living activities such as: standing up, sitting down, walking, reading a magazine, *etc.* Consistently, experiments show that our representation enhances the discriminative power of the tracklet descriptors and the bag-of-words model, and improves action recognition performance.

Sample video frames with extracted tracklets and estimated head positions are presented in Figure 30 .

This work has been published in [32].

6.12.1. Acknowledgments

This work was supported by the Région Provence-Alpes-Côte d’Azur. However, the views and opinions expressed herein do not necessarily reflect those of the financing institution

6.13. 3D Trajectories for Action Recognition Using Depth Sensors

Participants: Michal Koperski, Piotr Bilinski, François Brémond.

keywords: action recognition, computer vision, machine learning, 3D sensors

The goal of our work is to extend recently published approaches ([61], [62], [32], [90]) for Human Action Recognition to take advantage of the depth information from 3D sensors.



Figure 30. Sample video frames with extracted tracklets and estimated head positions for the KTH (first row), ADL (second row) and our locally collected dataset (third row).

We propose to add depth information to trajectory based algorithms ([32], [90]). Currently mentioned algorithms compute trajectories by sampling video frames and then tracking points of interest - creating the trajectory. Our contribution is to create even more discriminative features by adding depth information to previously detected trajectories. In our work we propose methods to deal with noise and missing measurements in depth information map. Such computed 3D trajectories, combined with other appearance features (HOG, HOF), are subject to a Bag of Words model and SVM classifier.



Figure 31. Visualization of MSR Daily Activity 3D data set. Left : video input frame; Middle : frame with detected trajectories (red = static points, green = detected trajectories); Right : corresponding depth map.

The evaluation of our method was conducted on the "Microsoft Daily Activity3D" data set [91] which consist of 16 actions (drink, eat, read book, call cellphone, write on a paper, use laptop etc.) performed by 10 subjects.

The experiments showed that adding depth information to Dense Trajectories descriptor [90] gave gain in efficiency 57.72% to 64.12%. The mentioned work is going to be submitted in December 2013.

6.14. Unsupervised Sudden Group Movement Discovery for Video Surveillance

Participants: Sofia Zaidenberg, Piotr Bilinski, François Brémond.

keywords: Sudden Group Movement Discovery, Video Surveillance.

In this work we address the problem of discovering “sudden” movements in video surveillance videos. We propose an unsupervised approach which automatically detects quick motions in a video, corresponding to any action. A set of possible actions is not required and the proposed method successfully detects potentially alarm-raising actions without training or camera calibration. Moreover the system uses a group detection and event recognition framework to relate detected sudden movements and groups of people, and provides a semantic interpretation of the scene. We have tested our approach on a dataset of nearly eight hours of videos recorded from two cameras in the Parisian subway for a European Project. For evaluation we annotated one hour of sequences containing 50 sudden movements. Our system, if parametrized to a high sensitivity, detects 100% of what the annotator considered as sudden potentially dangerous events, with a false positive rate of 21.2%. Setting the sensitivity to lower values we decrease the false positive rate to only 5.3% but we also decrease the success rate to 76%. An example of an unusual sudden movement annotated by a human and detected by our approach is presented in Figure 32. This work has been published in [49].

6.14.1. Acknowledgments

This work was supported by the Région Provence-Alpes-Côte d’Azur and by the European Community’s Seventh Framework Programme FP7/2007-2013 - Challenge 2 - Cognitive Systems, Interaction, Robotics - under grant agreement number: 248907-VANAHEIM. However, the views and opinions expressed herein do not necessarily reflect those of the financing institution.

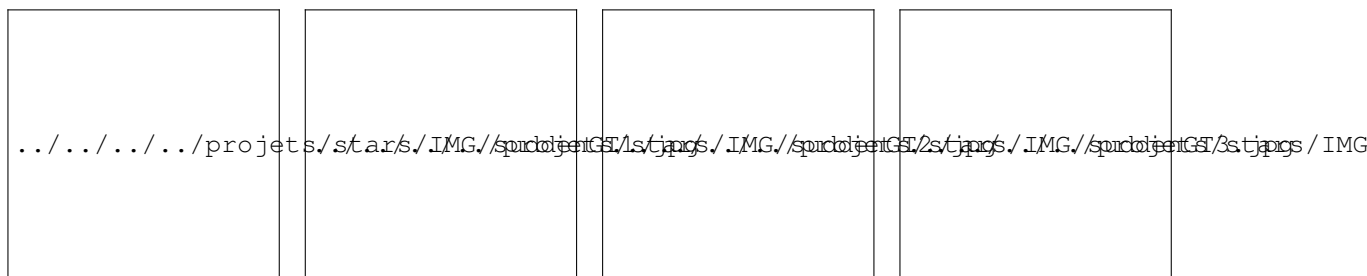


Figure 32. Example of an unusual sudden movement detected by our approach.

6.15. Group Behavior Understanding

Participants: Carolina Gárate, Sofia Zaidenberg, Julien Badie, François Brémond.

The goal is to recognize group behavior from videos. Dangerous and criminal behaviors are mostly observed within groups of people. The idea is to detect potentially dangerous situations while they are happening in the context of underground railway station security.

keywords: group tracking, scene understanding, group behavior recognition, video surveillance, event detection.

This research work considers a process consisting of 5 consecutive steps for video processing. The steps are: 1) segmentation, 2) blob detection, 3) physical objects tracking, 4) group tracking and 5) behavior recognition. Here, we are focussing on the last two phases: group tracking and behavior recognition.

The group tracking approach characterizes a group through three features: the average of the intra-object distance, the average standard deviations of speed and direction. The input for this algorithm is a set of trajectories for the physical objects (output of the stage 3: physical objects tracking) tracked by the algorithm described in [64]. The trajectories are processed using Mean-Shift clustering to create more reliable groups, see Figure 33 .

The behavior recognition approach identifies 2 steps: knowledge modeling and the event recognition algorithm. The ontology is implemented with the ScReK declarative language [94]. The grammar describes the objects and events using the extended BNF (Backus Naur Form) representation.

We process large amounts of long video surveillance data from Paris and Turin underground railway station to perform statistical analysis. This analysis automatically brings forward data about the usage of the station and the various behaviors of groups for different hours of the day. We present the results and interpretation of one month of processed data from a video surveillance camera in Turin subway.

One of the measures obtained in the experimentation is the agitation level which is represented by the variation of the size of the bounding box of a group. We consider 3 categories from *no agitation* ("Calm_Group", having a bounding box with stable size) to *little agitation* ("Active_Group") to *high agitation* ("Lively_Group", the bounding box's size varies a lot, meaning that group members move around more often). Figure 34 shows that most of the time, this middle category predominates. Groups are neither too calm, nor too agitated. Moreover, it is more common for a group to be lively rather than calm. The rest of the results obtained were presented in [54].

6.16. Evaluation of an Activity Monitoring System for Older People Using Fixed Cameras

Participants: Carlos F. Crispim-Junior, Baptiste Fosty, Vasanth Bathrinarayanan, Salma Zouaoui-Elloumi, Monique Thonnat, François Brémond.

keywords: 2D-RGB cameras, RGB-D cameras, model-based activity recognition, older people

We have continued the evaluation of our model-based algorithm for complex activity recognition, now extending it to a larger dataset containing 38 older people participants undertaking instrumental activities of daily living (IADL) during 15 minutes (570 min. in total). The recordings have taken place in the observation room of the Memory Center of Nice hospital. Figure 35 presents the algorithm performance based on data obtained from a 2D-RGB video camera. A summary of the recognized activities (e.g., duration, frequency) is produced at the end of the event recognition task to be provided to doctors as a basis for the assessment of patient performance on IADL. This approach description and the evaluation results are published in 2013 AVSS Conference (see details in [36]). Figure 36 illustrates an example of a patient being monitored. Blue dots illustrates previous positions of the person in the scene.

The proposed approach has been also evaluated using a RGB-D camera, as this camera increases the robustness of the monitoring system against environment illumination changes and also eases the deployment of the system by providing real 3-D information on the scene. The evaluation of the RGB-D-based activity monitoring system has been published in [38]. A live demonstration of this system has also been presented and applied in the scope of Dem@care project (a FP7 project devoted to multi-sensor older people monitoring) in the exhibition held in November 2013 in conjunction with the 2013 edition of the ICT (Information Communication Technologies) Conference in Vilnius - Lithuania.

6.17. A Framework for Activity Detection of Older People Using Multiple Sensors

Participants: Carlos F. Crispim-Junior, Qiao Ma, Baptiste Fosty, François Brémond, Monique Thonnat.

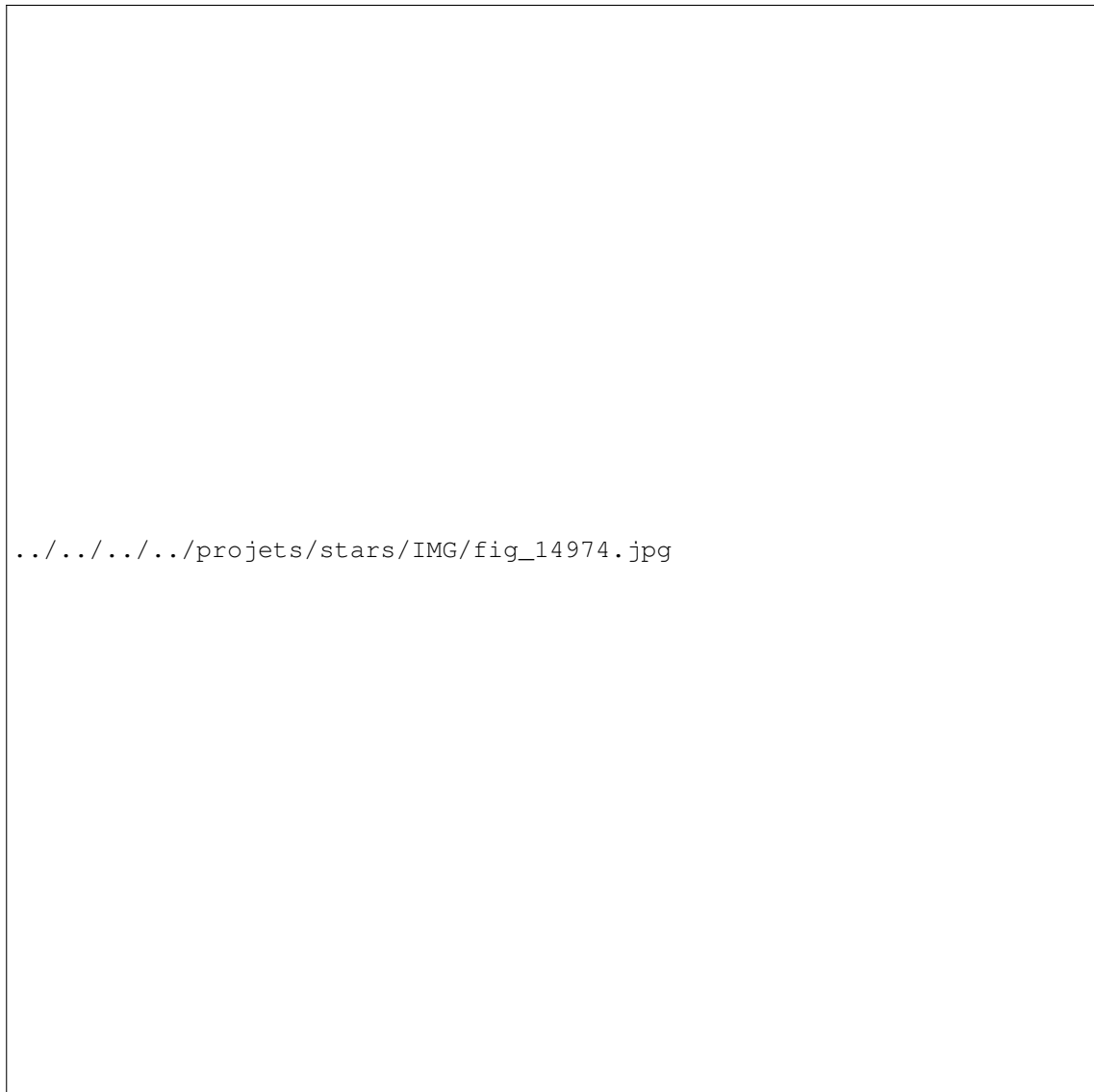


Figure 33. Illustration of a still group: in the right entrance zone a group of subway security staff is standing still.



Figure 34. Comparison of speed of groups and variation of group's bounding boxes during the day.



Figure 35. Evaluation of Algorithm performance on 38 patient video recordings using a RGB camera



Figure 36. Example of a patient been monitored by the described system

keywords: model-based activity recognition, multi-sensor, Dempster-Shafer, Evidence Theory, older people.

We have extended our framework for multi-sensor activity detection by proposing a probabilistic approach for mutually exclusive activity conflict scenario. The proposed approach pre-learned a coefficient of reliability of each sensor with respect to each activity. The combination of the activities detected by multiple sensors is performed using the Dempster-Shafer evidence theory with an adapted combination rule based on runtime data from the sensor and the pre-computed coefficients of reliability. The combination of activities detected by multiple sensors can be performed in an iterative fashion taking into account several sensor contributions (see Fig.37). Tab. 5 presents the early results of the proposed probabilistic method at combining activities detected using RGB and RGB-D cameras. Results are presented individually for each camera and for the proposed approach.



Figure 37. Probabilistic Approach Combination Scheme

The proposed fusion scheme performs better than the camera individual process in most of cases even in the presence of noise (see the RGB-D individual result of sensitivity for standing posture detection). The complete evaluation of the proposed approach is published in [43]. The developed probabilistic approach is now integrated into our previously developed framework for multi-sensor activity modeling. The new framework version allows experts to precisely define the sensors which will be used to detect each activity, or to automatically (and then probabilistic) combine multiple instances of (conflicting) activities detected by different sensors. The new framework proposal for multi-sensor activity detection has been published in [37].

6.18. Walking Speed Detection on a Treadmill using an RGB-D Camera

Participants: Baptiste Fosty, François Brémond.

Table 5. Performance of the proposed probabilistic approach on posture detection

Posture	Standing		Sitting	
	Precision	Sensitivity	Precision	Sensitivity
Sensor				
RGB	84.29	69.41	79.82	91.58
RGB-D	100.00	36.47	86.92	97.89
Fusion	82.35	91.30	91.04	95.31

keywords: RGB-D camera analysis, older people, serious games

Within the context of the Az@Game project, we have studied the potential of the RGB-D camera (Red Green Blue + Depth) for the control of a serious game dedicated to older people suffering from Alzheimer disease. Within this game, the patient is invited to perform some physical and cognitive tasks (walking on a treadmill at different speeds, performing gestures to control his/her character in the game, managing money) in order to assess the evolution of the disease, to stimulate them and improve their abilities. In this context, one of our goal is the computation of the walking speed of a person on a treadmill.

The proposed solution is divided into three distinct steps :

- people detection and tracking using a background subtraction algorithm.
- feet detection : based on the cloud of 3D points of the person, and more particularly on the lower body part, the axis of each leg is computed. The corresponding foot is then defined as the projection of the lowest point of the leg on the leg axis (see Fig. 38 , right picture).
- speed computation : computed from the successive positions of the feet, more precisely from the distances between the feet (see Fig. 38 , left graph representing the distance between the feet). Each time this distance reaches a local maximum (corresponding to each step), the current speed is computed as the maximum over the time since the last step. The speed is then averaged with the previous computed speed to smooth the values (see Fig. 38 , middle graph representing the speed in function of time).

Concerning the results, the first experimentation of the algorithm shows that, qualitatively, the computed walking speed is proportional to the real speed. Future work will focus on experimenting the proposed system on a larger scale (different people, location, etc.) in order to validate the approach. We will also focus on trying to detect arm gestures to have more control on the serious game.

About the Dem@Care project and the previous work on the activity recognition system developed to extract automatically and objectively evidences of early symptoms of Alzheimer's disease for older people, this contribution has been published at ASROB 2013, Workshop on Assistance and Service Robotics in a Human Environment (see [38]).

6.19. Serious Game for older adults with dementia

Participants: Minh Khue Phan Tran, François Brémond.

keywords: human-machine interaction, serious games, Alzheimer, activity recognition

Serious Games is carried out within the framework of the *Az@GAME project*. This project is to create games offering patient-oriented scenarios so as to measure their health progress, improve their physical fitness, stimulate their cognitive abilities, and help maintain their social skills. The main objective is to design a system interacting with older adults suffering from Alzheimer's or Alzheimer's related diseases. The three challenges in designing the system are:

- **perception's precision** : how does the system choose the "*best moments*" to interact with a patient ?
- **attractive-visualization** : how does the system make the patients comfortable?
- **ease of interaction** : how can it optimize the interaction with the patients ? In what way ?



Figure 38. Walking speed computation on a treadmill. The left graph is the representation of the distance between the feet as a function of time. The middle graph is the representation of the speed of the person as a function of time. The right picture is the RGB-D camera view with the people detection and current speed. The two yellow circles show the positions of the detected feet.

The first prototype is under development. The system consists of two parts: Recognition and Interaction . Each component requires a 3D camera (Microsoft Kinect for the recognition component and Asus Xtion Pro Live Camera for the interaction component). The recognition part consists in observing the scene and deciding the best time to interact with a patient via the Asus camera. It uses the SUP framework. Afterwards, the interactive system tries to engage the patient via an interface and through Microsoft Kinect, the patient can interact with the interface using voice or gesture. The interface is designed with the Unity 3D game engine.

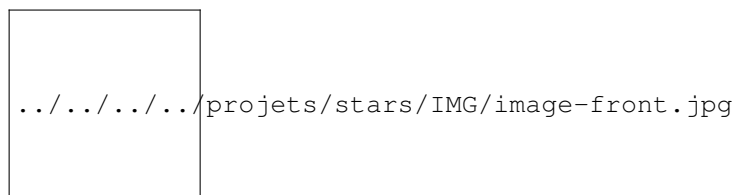


Figure 39. Example of a game and its gesture interface.

The first experiment will be conducted in the coffee area. The aim is to test the functionality of the system and measure its accuracy and effectiveness. The system will observe the scene and invite people who are getting coffee or taking a break to play the game. Depending on the interaction with the person, the system will offer different scenarios. Videos will be recorded, with the consent of the subject, in order to evaluate the effectiveness of system. The recorded videos and meta-data provided by SUP will be evaluated to determine the accuracy of the system.

6.20. Unsupervised Activity Learning and Recognition

Participants: Serhan Cosar, Salma Zouaoui-Elloumi, François Brémond.

keywords: Unsupervised activity learning, hierarchical activity models, monitoring older people activities

The aim of this work is to monitor older people activities at hospital or at home environment in an unsupervised manner. We have extended the work in [81] that was initially based on user interface to label activities and proposed a new strongly unsupervised framework. It enables the discovery, modeling, and recognition of activities without user interaction. One advantage of this approach is that the framework learns individual behavioral patterns in unstructured scenes without restraining people to act based on a manually pre-defined model. The Figure 40 -(a) presents the off-line learning steps of this framework. It takes as input a set of videos pre-processed to obtain trajectory information of people in the scene. Using the trajectory information (global position and pixel tracklets of body parts) of each person, zones of interest, where the person performs an activity, are learned. As in [81], we obtain three levels of zones using k -means clustering for different k values. The obtained zones are used to create different levels of events from the coarser to the finer ones. Based on the three levels of events, a hierarchical model of activities is learned to represent each action (Figure 40 -(a)). For each new video, an on-line recognition process is performed by using the previously learned zones and models of activities (Figure 40 -(b)).

We have evaluated the performance of the unsupervised algorithm for RGB-D and 2D camera using 8 videos and 10 videos, respectively. Half of the videos are used for learning zones and models of activities. Videos are recorded in CHU Nice hospital while older people are visiting their doctors and include the following actions: “talking on the phone”, “preparing drugs”, “sitting at the table”, “preparing tea”, “looking at the bus map”, “watching TV” and “paying bill”. The trajectory information for 2D camera is obtained using the method in [81]. For RGB-D camera, we have used the person detection algorithm in [79] and tracking algorithm in [33]. The results obtained for both cameras are presented in Table 6 and Table 7 , respectively. We have used the following metrics to evaluate the framework: TP: True positive, FP: False positive, FN: False Negative,



Figure 40. The flow diagram of the unsupervised activity recognition framework: (a) off-line learning phase and (b) on-line recognition phase

Sensitivity and Precision. According to the trajectory information, sometimes k -means clustering produces zones that are actually union of more than one zones. For such cases, we have combined the actions and presented as one single action.

Table 6. The recognition results obtained by using the 2D camera.

Actions	Instances	TP	FP	FN	Sensitivity(%)	Precision (%)
Paying bill	13	5	0	8	38.46	100
Preparing drugs	7	5	5	2	71.42	50
Looking at bus map+Watching TV	21	6	3	15	28.57	66.66
Sitting at the table	18	6	10	12	33.33	37.5
Talking on the phone	23	17	1	6	73.91	94.44
Preparing tea	23	11	3	12	47.82	78.57

Table 7. The recognition results obtained by using the RGB-D camera.

Actions	Instances	TP	FP	FN	Sensitivity(%)	Precision (%)
Paying bill + Watching TV	13	12	8	1	92.3	60
Preparing drugs	5	5	0	0	100	100
Looking at bus map	9	9	10	0	100	47.36
Sitting at the table	8	4	34	4	50	10.52
Talking on the phone	14	13	1	1	92.85	92.85
Preparing tea	16	9	5	7	56.25	64.28

As it can be seen in the tables, we obtain higher recognition rates by using the information coming from RGB-D camera.

Table 6 shows that for “talking on the phone” and “preparing drugs” actions occurring in two distant zones, using 2D camera gives high recognition rates (higher than 70 %). However, the actions “looking at bus map”, “watching TV” and “sitting at the table” are misclassified (low TP and high FP). Since the zones of these actions are very close to each other, the actions occurring in the borders are not well recognized. The reason of high FN is due to the problems in detection and tracking with 2D video cameras. The process of trajectory extraction described in [81] sometimes fails to track people. Because of the inadequate trajectory information, we have many FNs. Therefore, a better detection can considerably enhance the recognized actions.

By using the information coming from RGB-D camera, except for “sitting at the table” and “preparing tea” actions, we achieve high level of recognition rates (Table 7). However, similar to 2D camera, the recognition of “sitting at the table”, “paying bill” and “watching TV” actions fails because the learned zones in the scene are very close to each other. Hence, we have many false positives (FP) and false negatives (FN) for “sitting at the table” and “preparing tea” actions.

In the light of the preliminary experimental results, we can say that this unsupervised algorithm has a potential to be used for automated learning of behavioral patterns in unstructured scenes, for instance in home care environment for monitoring older people. Since the current framework does not require the user interaction to label activities, an evaluation process on big datasets will be easily performed. The proposed framework gives one action at each zone in an unsupervised way. We are currently focusing on refining the actions for each

zone by using the pixel tracklets of the person's body parts. This will be achieved by performing clustering among activity models. As an example, the action of "sitting at the table" will be decomposed to "reading newspaper while sitting at the table" and "distributing cards while sitting at the table".

6.21. Extracting Statistical Information from Videos with Data Mining

Participants: Giuseppe Donatiello, Hervé Falciani, Duc Phu Chau, François Brémond.

keywords: video data mining, activity recognition, clustering techniques

Objective

Manual video observation is becoming less practical due to growing size of data. To tackle this problem, we have built a system to retrieve videos of interest thanks to an index based on activities recognized in an automated manner. We automatically detect activities in videos by combining data mining and computer vision to synthesize, analyze and extract valuable information from video data.

Approach

Our research introduces a new method for extracting statistical information from a video. Specifically, we focus on context modeling by developing an algorithm that automatically learns the zones in a scene where most activities occur by taking as input the trajectories of detected mobiles. Using K-means clustering, we define activity zones characterizing the scene dynamics, we can extract then people activities by relating their trajectories to the learned zones.

Results

To evaluate our system we have extended the OpenJUMP framework, an open source for Geographic Information System (GIS). The end user can have an overview of all activities of a large video, with the possibility of extracting and visualizing activities classified as usual or unusual. We have tested our approach on several videos recorded in subways in Turin (Italy) and Paris, as shown below, some examples of unusual activities (Figures 41, 42 and 43). The system has been showed in a live demonstration at RATP company in Paris for the European project Vanaheim (<http://www.vanaheim-project.eu/>).

6.22. SUP

Participants: Julien Gueytat, François Brémond.

keywords: SUP, Software, Video Processing

Presentation

SUP is a Scene Understanding Software Platform writtent in C++ designed for analyzing video content. (see Figure 44) SUP is splitting the workflow into several modules, such as acquisition, segmentation, etc., up to activity recognition. Each module has a specific interface, and different plugins implementing these interfaces can be used for each step of the video processing.

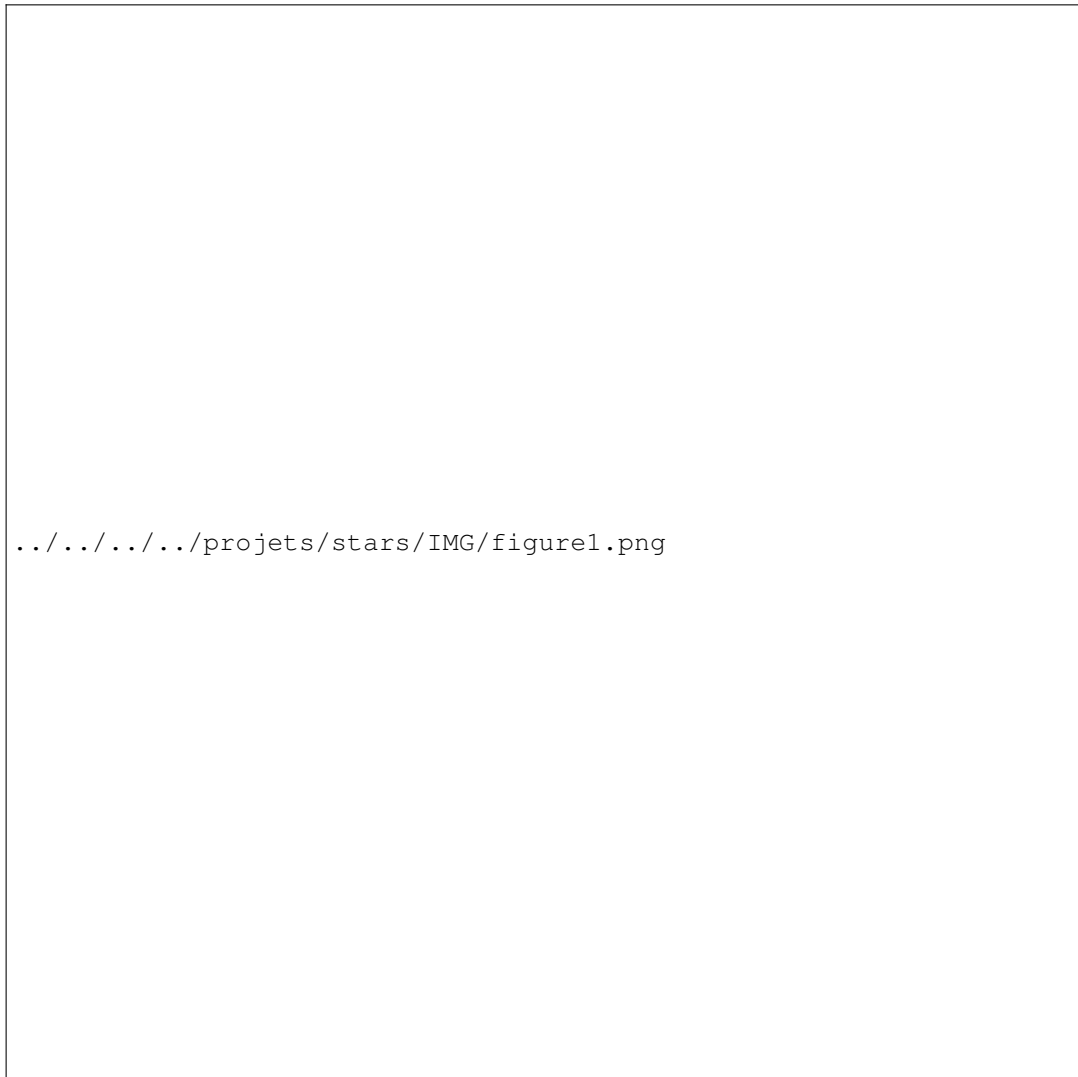


Figure 41. Results : three categories of discovered abnormal behaviors.

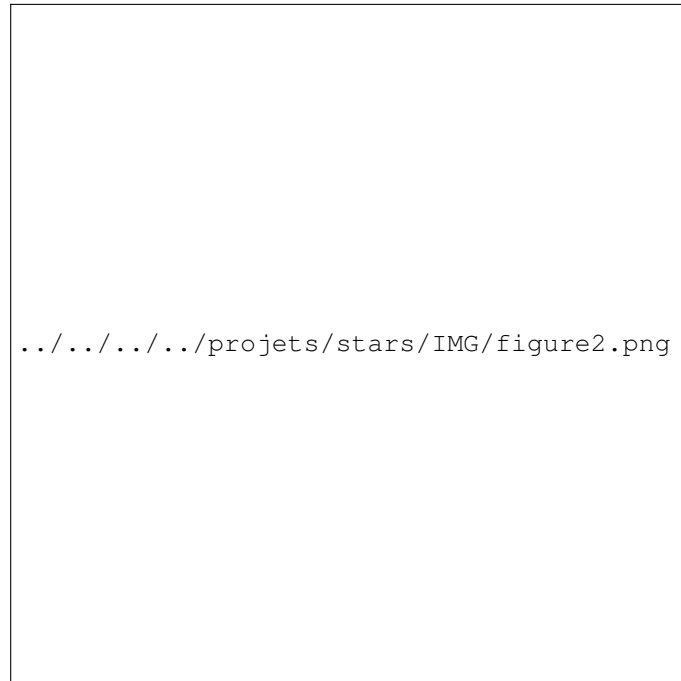


Figure 42. Trajectories and zones from camera M3114 in Paris (the yellow line is the trajectory selected by the user; the numbers represent the weight belonging to each segment : the higher, the more the people go through it).

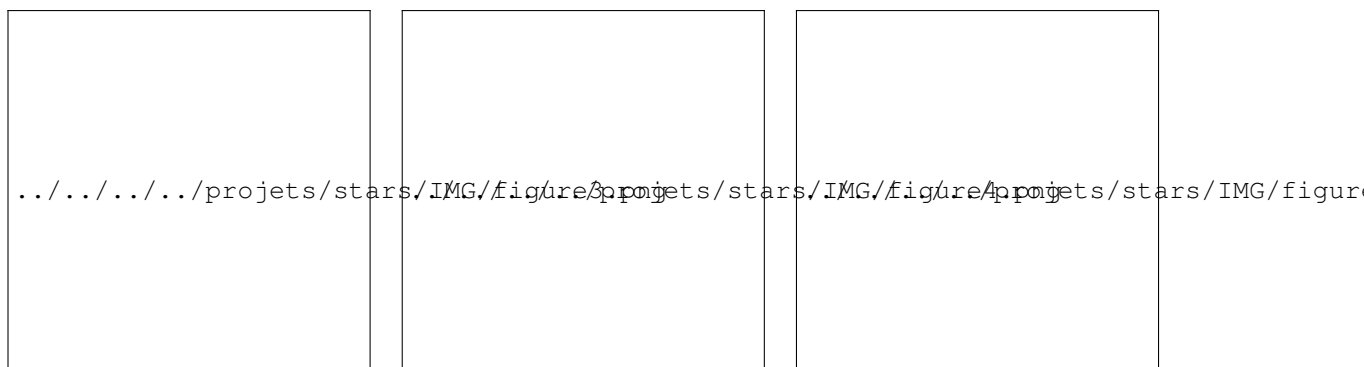


Figure 43. Left : Person sitting. Middle : Person standing for a long time. Right : Unusual path.



Figure 44. SUP workflow

The plugins cover the following research topics:

- algorithms : 2D/3D mobile object detection, camera calibration, reference image updating, 2D/3D mobile object classification, sensor fusion, 3D mobile object classification into physical objects (individual, group of individuals, crowd), posture detection, frame to frame tracking, long-term tracking of individuals, groups of people or crowd, global tacking, basic event detection (for example entering a zone, falling...), human behaviour recognition (for example vandalism, fighting,...) and event fusion;
- languages : scenario description, empty 3D scene model description, video processing and understanding operator description;
- knowledge bases : scenario models and empty 3D scene models;
- algorithms of 2D & 3D visualisation of simulated temporal scenes and of real scene interpretation results;
- algorithms for evaluation of object detection, tracking and event recognition;
- learning techniques for event detection and human behaviour recognition;
- algorithms for image acquisition (RGB and RGBD cameras) and storage;
- algorithms for video processing supervision;
- algorithms for data mining and knowledge discovery;
- algorithms for image/video indexation and retrieval.

The software is already widely disseminated among researchers, universities, and companies:

- PAL Inria partners using ROS PAL Gate as middleware
- Nice University (Informatique Signaux et Systèmes de Sophia), University of Paris Est Créteil (UPEC - LISSI-EA 3956)
- European partners: Lulea University of Technology, Dublin City University,...
- Industrial partners: Toyota, LinkCareServices, Digital Barriers

And new sites are coming: EHPAD Valrose, Institut Claude Pompidou, Delvalle and Biot.

Improvements

Our team focuses on developing a Scene Understanding Platform (SUP). This platform has been designed for analyzing video content. SUP is able to recognize events such as 'falling', 'walking' of a person. We can easily build new analyzing systems thanks to a set of algorithms also called plugins. The order of those plugins and their parameters can be changed at run time and the result visualized on a dedicated GUI. This platform has many more advantages such as easy serialization to save and replay a scene, portability to Mac, Windows or Linux, and easy deployment to quickly setup an experimentation anywhere. All those advantages are available since we are working together with the Inria software developer team SED. Many Inria teams are pushing together to improve a common Inria development toolkit DTK. Our SUP framework is one of the DTK-like framework developed at Inria.

Currently, the OpenCV library is fully integrated with SUP. OpenCV provides standardized datatypes, a lot of video analysis algorithms and an easy access to OpenNI sensors such as the Kinect or the ASUS Xtion PRO LIVE.

Updates and presentations of our framework can be found on our team website <https://team.inria.fr/stars/software>. Detailed tips for users are given on our Wiki website <http://wiki.inria.fr/stars> and sources are hosted thanks to the software developer team SED.

6.23. Model-Driven Engineering for Activity Recognition

Participants: Sabine Moisan, Jean-Paul Rigault, Luis Emiliano Sanchez.

keywords: Feature Model Optimization, Software Metrics, Requirement specification, Component-based system, Dynamic Adaptive Systems, Model-Driven Engineering, Heuristic Search

The domain of video surveillance (VS) offers an ideal training ground for Software Engineering studies, because of the huge variability in both the surveillance tasks, the video analysis algorithms and the context. Such systems require run time adaptation of their architecture to react to external events and changing conditions in their context of execution.

The feature model formalism is widely used to capture variability, commonalities and configuration rules of software systems. We thus use feature modeling to represent the variability of both the specification and component views of video surveillance systems. We also include cross-tree constraints that formalize extra feature dependencies.

Based on this feature model, we can both select an initial system configuration at deployment time and dynamically adapt the current configuration at run time. This year we focused on runtime adaptation, from feature model to running components.

6.23.1. Configuration Adaptation at Run Time

In the continuation of our work on metrics on feature models, we have integrated a configuration selection algorithm in our feature model manager. Context changes or user interactions imply to dynamically reconfigure the model (selecting or deselecting features). Following *model at run time* techniques, we are able to determine the set of valid configurations to apply in a new execution context. Since only one configuration can be applied at a given time, the role of the selection algorithm is to select the “best” one.

To this end we enriched our feature representation with a set of *quality attributes* that correspond to a monotonic quantification of interesting aspects of the system quality. Examples are response time, accuracy, availability, performance, component switching time, etc. The configuration selection algorithm optimises a cost function, a linear weighted combination of the quality attributes. Thus we can rank the possible valid configurations and choose an optimal one. Our algorithm is a variant of the Best-First Search algorithm, a heuristic graph search technique. It starts with the set of valid configurations, which is a feature model where some features are *unselected*. Then it performs a systematic search in a graph where nodes are configurations and edges are selections or deselections of unselected features. The goal is to obtain a full configuration (one without unselected features) optimizing the cost function. The algorithm is parameterized with different strategies and associated heuristics with different optimality and efficiency characteristics.

Search strategies decide which node to visit next. We choose two well-known informed strategies that rely on heuristic functions as choice criteria. First we used a variant of the A* algorithm, BF*, but with a node-cost function instead of a path-cost one; it favors optimality over efficiency. Second, we implemented a Greedy Best-First Search (GBFS) strategy, where the next visited node is the best successor of the current one; it favors efficiency over optimality.

Computing the exact value of the cost function for a partial configuration is too expensive. We thus use heuristics to obtain a quick *estimate*. We have tested two sorts of heuristics. The simplest one, H_A , ignores the differences between the various sorts of groups (AND, OR, XOR) in the feature model and does not consider cross-tree constraints; it is fast but not very accurate. The second one, H_B , just drops the cross-tree constraints; it is thus more accurate, yet at a higher cost.

We have run experiments using large (randomly generated) feature models and compared completeness, optimality and efficiency of the selection algorithm, with different combinations of strategies and heuristics [42]. From our experiments, the GBFS strategy with heuristics H_B appears as the ideal option for real time systems that have to adapt in bounded time. This strategy ensures polynomial time complexity and guarantees optimality over 90%, which is good enough for our purpose (see figure 45). On the other hand, BF* strategy with heuristics H_B is ideal for offline decisions, such as defining the initial configuration of a system. Although this search strategy takes a significant time to compute, this is acceptable at deployment time to obtain the optimal configuration.

6.23.2. Run Time Components

When a configuration has been chosen, we must implement it with real components. We consider a configuration of a video-surveillance processing chain as a set of running components, that can be tuned, removed,



Figure 45. Optimality comparison of heuristics using GBFS strategy with respect to the number of attributes in the cost function

added, or replaced dynamically, in response to events. To apply such configuration changes, we need a way to represent and dynamically manipulate the components themselves.

In a first attempt, we used an OSGi-like C++ framework (SOF, Service Oriented Framework). However, SOF did not really fulfilled our needs. First, SOF is the only C++ OSGi framework that we could find and its C++ implementation deserves some improvement. Moreover, like OSGi, it relies on the notion of “service”, as can be found in Web applications, but which does not really fit our real time requirements. This notion of service is not our concern and makes programming more complicated than necessary.

Thus, we decided to define our own component module and to integrate it in a multi-threaded layer, easy to use for our end-users who are video system developers. Each component runs by default in its own thread and communicates with other components through standardized communication channels. Our goal is to provide end-users with simple patterns to package their video codes into components. Thus we hide as much as possible the technical details such as threading synchronization, data exchange, and mechanisms for component management (replacement, tuning...) ensuring a continuous process.

We are currently setting up this framework on a simple video detection pipeline with OpenCV-based components. Then we shall integrate it within our Model at Run Time architecture.

6.24. Scenario Analysis Module

Participants: Annie Ressouche, Daniel Gaffé, Narjes Ghrairi, Sabine Moisan, Jean-Paul Rigault.

Keywords: Synchronous Modelling, Model checking, Mealy machine, Cognitive systems.

To generate activity recognition systems we supply a scenario analysis module (SAM) to express and recognize complex events from primitive events generated by SUP or other sensors. The purpose of this research axis is to offer a generic tool to express and recognize activities. Genericity means that the tool should accommodate any kind of activities and be easily specialized for a particular framework. In practice, we propose a concrete language to specify activities in the form of a set of scenarios with temporal constraints between scenarios. This

language allows domain experts to describe their own scenario models. To recognize instances of these models, we consider the activity descriptions as synchronous reactive systems [80] and we adapt usual techniques of synchronous modelling approach to express scenario behaviours. This approach facilitates scenario validation and allows us to generate a recognizer for each scenario model.

Since last year, we relied on CLEM (see section 6.25) synchronous language to express the automata semantics of scenario models as Boolean equation systems. This year, we continue our research in this direction and we are studying a specific semantics of SAM language operators that translates any SAM program into Boolean equation system. Therefore, we will benefit from CLEM compilation technique to generate recognizer for each scenario model.

This year we focus on the definition of an execution machine able to transform asynchronous events coming from SUP or other devices into synchronous significant events feeding recognition engines generated by SAM. The execution machine can listen three types of asynchronous events: SUP events, Boolean sensors, sampled sensors and pulse train sensors. According to the sampling period of each sensor, the execution machine builds the significant events defining the synchronous logical instants which trigger the reaction of the scenario recognition engine. Thanks to the synchronous approach, scenario recognition engines are able to dynamically express the expected synchronous events of the next step; the execution machine takes into account of this information to filter relevant events. We perform several tests with real SUP data sets and the execution machine has a convincing behaviour (see [55]). To complement this work, we will integrate a notion of incompatible events which will make the execution machine more efficient and robust.

6.25. The Clem Workflow

Participants: Annie Ressousche, Daniel Gaffé, Joel Wanza Weloli.

Keywords: Synchronous languages, Synchronous Modelling, Model checking, Mealy machine.

This research axis concerns the theoretical study of a synchronous language LE with modular compilation and the development of a toolkit (see Figure 9) around the language to design, simulate, verify and generate code for programs. The novelty of the approach is the ability to manage both modularity and causality. This year, we mainly work on the implementation of new theoretical results concerning the foundation of LE semantics. We also design a new simulator for LE programs which integrates our new approach.

First, synchronous language semantics usually characterizes each output and local signal status (as present or absent) according to input signal status. To reach our goal, we defined a semantics that translates LE programs into equation systems. This semantics bears and grows richer the knowledge about signals and is never in contradiction with previous deduction (this property is called constructiveness). In such an approach, causality turns out to be a scheduling evaluation problem. We need to determine all the partial orders of equation systems and to compute them, we consider a 4-valued algebra to characterize the knowledge of signal status (unknown, present, absent, overknown). In [69], we chosen an algebra which is a bilattice and we show that it is well suited to solve our problem. It is a new application of general bilattice theory [70]. This year, this approach has been improved, validated in CLEM compiler and published in [39]. Our compilation technique needs to represent Boolean equation systems with Binary Decision Diagrams (BDD) and we study and design a specific BDD library well suited to ours needs. From a practical point of view, we integrate new operators in LE language (sustain until, no emit, strong abort). We focus on automata extension which can consider now three types of transition: weak transition, strong transition and normal termination transition.

Second, in CLEM, we generate an independent intermediate code (LEC) before specific target generations. This code represents the semantics of programs with 4-valued equation systems. In our design flow, we need to simulate programs at this level. This year, we design the CLES simulator which interprets LEC. The actual version don't integrate the data part of the language and we plan to do this integration.

6.26. Multiple Services for Device Adaptive Platform for Scenario Recognition

Participants: Annie Ressousche, Daniel Gaffé, Mohammed Cherif Bergheul, Jean-Yves Tigli.

Keywords: Synchronous Modelling, Model checking, Mealy machine, Ubiquitous Computing.

The aim of this research axis is to federate the inherent constraints of an activity recognition platform like SUP (see section 5.1) with a service oriented middleware approach dealing with dynamic evolutions of system infrastructure. The Rainbow team (Nice-Sophia Antipolis University) proposes a component-based adaptive middleware (WComp [88], [87], [73]) to dynamically adapt and recompose assemblies of components. These operations must obey the "usage contract" of components. The existing approaches don't really ensure that this usage contract is not violated during application design. Only a formal analysis of the component behaviour models associated with a well sound modelling of composition operation may guarantee the respect of the usage contract.

The approach we adopted introduces in a main assembly, a synchronous component for each sub assembly connected with a critical component. This additional component implements a behavioural model of the critical component and model checking techniques apply to verify safety properties concerning this critical component. Thus, we consider that the critical component is validated.

In [84], [83], we showed that an efficient means to define the synchronous components which allow to validate critical component behaviours, is to specify them with Mealy machines. Previously, we used a classical synchronous language (Lustre) to specify synchronous components, but the integration of the synchronous component code into WComp was not straightforward because Lustre compiler is not opened and cannot integrate new target code needed by WComp. This year, we supply GALAXY automata editor to express Mealy machines and we extend AUTOM2CIRCUIT compiler to generate the internal code of WComp (C#). AUTOM2CIRCUIT is a tool developed by D. Gaffé since several years which compiles an explicit representation of automata into Boolean Mealy machine and generate a large and opened set of targets. This work is a preliminary study to integrate this generation of C# into CLEM.

TITANE Team

6. New Results

6.1. Analysis

6.1.1. Detecting Parametric Objects in Large Scenes by Monte Carlo Sampling

Participants: Yannick Verdie, Florent Lafarge.

Point processes constitute a natural extension of Markov Random Fields (MRF), designed to handle parametric objects. They have shown efficiency and competitiveness for tackling object extraction problems in vision. Simulating these stochastic models is however a difficult task. The performance of existing samplers are limited in terms of computation time and convergence stability, especially on large scenes. We propose a new sampling procedure based on a Monte Carlo formalism [11]. Our algorithm exploits the Markovian property of point processes to perform the sampling in parallel. This procedure is embedded into a data-driven mechanism so that the points are distributed in the scene as a function of spatial information extracted from the input data. The performance of the sampler is analyzed through a set of experiments on various object detection problems from large scenes, including comparisons to the existing algorithms. The sampler is also evaluated as an optimization algorithm for MRF-based labeling problems (Figure 1).

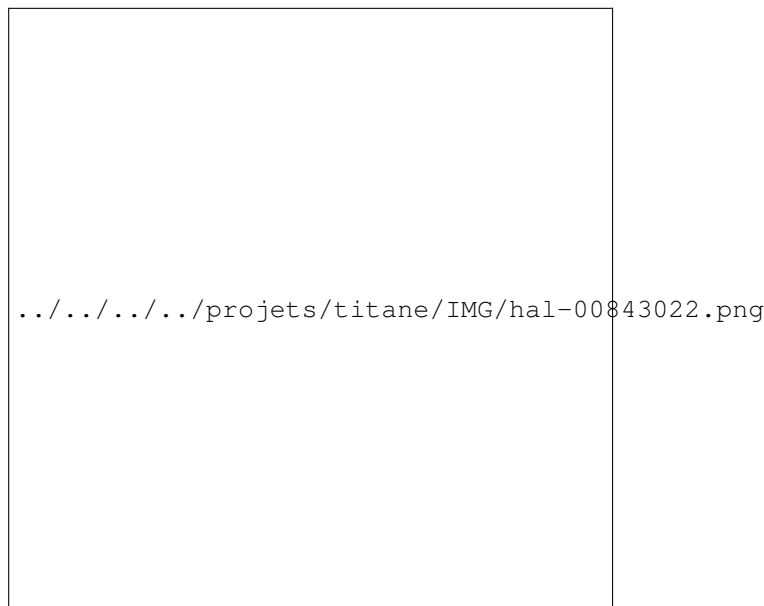


Figure 1. Detection and modeling of trees from large-scale Lidar scans by our parallel Monte Carlo sampler.

6.1.2. Recovering Line-networks in Images by Junction-Point Processes

Participant: Florent Lafarge.

In collaboration with Dengfeng Chai (Zhejiang University, China) and Wolfgang Forstner (University of Bonn, Germany).

We tackle the automatic extraction of line-networks from images. Appearance and shape considerations have been deeply explored in the literature to improve accuracy in presence of occlusions, shadows, and a wide variety of irrelevant objects. However most existing work has ignored the structural aspect of the problem. We present an original method which provides structurally-coherent solutions [13]. Contrary to the pixel-based and object-based methods, our result is a graph in which each node represents either a connection or an ending in the line-network. Based on stochastic geometry, we develop a new family of point processes consisting in sampling junction-points in the input image by using a Monte Carlo mechanism. The quality of a configuration is measured by a probability density which takes into account both image consistency and shape priors. Our experiments on a variety of problems illustrate the potential of our approach in terms of accuracy, flexibility and efficiency (Figure 2).



Figure 2. Line-network extraction from images using a junction-point process.

6.2. Approximation

6.2.1. Integer-Grid Maps for Reliable Quad Meshing

Participants: David Bommès, Pierre Alliez.

In collaboration with Leif Kobbelt from RWTH Aachen.

Quadrilateral remeshing approaches based on global parametrization enable many desirable mesh properties. Two of those are (1) high regularity due to explicit control over irregular vertices and (2) smooth distribution of distortion achieved by convex variational formulations. In this work [2] we propose a novel convex Mixed-Integer Quadratic Programming (MIQP) formulation which ensures by construction that the resulting map is within the class of so called Integer-Grid Maps that are guaranteed to imply a quad mesh. In order to overcome the NP-hardness of MIQP we propose two additional optimizations: a complexity reduction algorithm and singularity separating conditions. While the former decouples the dimension of the MIQP search space from the input complexity of the triangle mesh, the latter improves the continuous relaxation, which is crucial for the success of modern MIQP optimizers. Our algorithm also enables the global search for high-quality coarse

quad layouts as illustrated in Figure 3, a difficult task solely tackled by insufficient greedy methodologies before.



Figure 3. Integer-grid maps for reliable quad meshing.

6.2.2. QEx: Robust Quad Mesh Extraction

Participant: David Bommes.

In collaboration with Leif Kobbelt from RWTH Aachen.

Among the class of quad remeshing techniques, the ones based on parameterization strive to generate an integer-grid map, i.e., a parametrization of the input surface in 2D such that the canonical grid of integer iso-lines forms a quad mesh when mapped back onto the surface in 3D. An essential, albeit broadly neglected aspect of these methods is the quad extraction step. This step is not a trivial matter: ambiguities induced by numerical inaccuracies and limited solver precision, as well as imperfections in the maps produced by most methods (unless costly countermeasures are taken) pose significant hurdles to the quad extractor. In this work [6] we present a method to sanitize a provided parametrization such that it becomes numerically consistent even with limited precision floating point arithmetic. We also devise a novel strategy to cope with common local fold-overs in the parametrization. We can generate all-quadrilateral meshes where otherwise holes, non-quad polygons or no output at all would have been produced like for the example in Figure 4.

6.2.3. Advanced Automatic Hexahedral Mesh Generation from Surface Quad Meshes

Participant: David Bommes.

In collaboration with Leif Kobbelt (RWTH Aachen).

A purely topological approach for the generation of hexahedral meshes from quadrilateral surface meshes of genus zero has been proposed by M. Müller-Hannemann: in a first stage, the input surface mesh is reduced to a single hexahedron by successively eliminating loops from the dual graph of the quad mesh; in the second stage, the hexahedral mesh is constructed by extruding a layer of hexahedra for each dual loop from the first stage in reverse elimination order. We introduce several techniques to extend the scope of target shapes of the



Figure 4. QEx: Robust Quad Mesh Extraction.

approach and significantly improve the quality of the generated hexahedral meshes [14]. While the original method can only handle almost-convex objects and requires mesh surgery and remeshing in case of concave geometry, we propose a method to overcome this issue by introducing the notion of concave dual loops in order to handle non-convex objects like the one displayed in Figure 5 . Furthermore, we analyze and improve the heuristic to determine the elimination order for the dual loops such that the inordinate introduction of interior singular edges, i.e., edges of degree other than four in the hexahedral mesh, can be avoided in many cases.

6.2.4. On the Equilibrium of Simplicial Masonry Structures

Participant: Pierre Alliez.

In collaboration with Mathieu Desbrun, Fernando de Goes and Houman Owhadi from Caltech.

We contributed a novel approach for the analysis and design of self-supporting simplicial masonry structures [4]. A finite-dimensional formulation of their compressive stress field is derived, offering a new interpretation of thrust networks through numerical homogenization theory. We further leverage geometric properties of the resulting force diagram to identify a set of reduced coordinates characterizing the equilibrium of simplicial masonry. We finally derive computational form-finding tools that improve over previous work in efficiency, accuracy, and scalability.

6.3. Reconstruction

6.3.1. Noise-Adaptive Shape Reconstruction from Raw Point Sets

Participants: Simon Giraudot, Pierre Alliez.

In collaboration with David Cohen-Steiner (GEOMETRICA project-team)



Figure 5. Advanced Automatic Hexahedral Mesh Generation from Surface Quad Meshes.

We devised a noise-adaptive shape reconstruction method specialized to smooth, closed shapes [7]. Our algorithm takes as input a defect-laden point set with variable noise and outliers, and comprises three main steps. First, we compute a novel noise-adaptive distance function to the inferred shape, which relies on the assumption that the inferred shape is a smooth submanifold of known dimension. Second, we estimate the sign and confidence of the function at a set of seed points, through minimizing a quadratic energy expressed on the edges of a uniform random graph. Third, we compute a signed implicit function through a random walker approach with soft constraints chosen as the most confident seed points computed in the previous step.

6.3.2. Surface Reconstruction through Point Set Structuring

Participants: Florent Lafarge, Pierre Alliez.

We present a method for reconstructing surfaces from point sets [8]. The main novelty lies in a structure-preserving approach where the input point set is first consolidated by structuring and resampling the planar components, before reconstructing the surface from both the consolidated components and the unstructured points. Structuring facilitates the surface reconstruction as the point set is substantially reduced and the points are enriched with structural meaning related to adjacency between primitives. Our approach departs from the common dichotomy between smooth/piecewise-smooth and primitive-based representations by gracefully combining canonical parts from detected primitives and free-form parts of the inferred shape (Figure 6).

6.3.3. Hybrid Multi-view Stereo for Modeling Urban Scenes

Participant: Florent Lafarge.

In collaboration with Renaud Keriven (Acute3D), Mathieu Bredif (IGN), and Hiep Vu (Ecole des Ponts ParisTech).

We present an original multi-view stereo reconstruction algorithm which allows the 3D-modeling of urban scenes as a combination of meshes and geometric primitives [9]. The method provides a compact model while preserving details: irregular elements are described by meshes whereas regular structures are described by



Figure 6. Structuring of a church.

canonical geometric primitives. We adopt a two-step strategy consisting first in segmenting the initial mesh-based surface using a multi-label Markov Random Field based model and second, in sampling primitive and mesh components simultaneously on the obtained partition by a Jump-Diffusion process. The quality of a reconstruction is measured by a multi-object energy model which takes into account both photo-consistency and semantic considerations (i.e. geometry and shape layout). The segmentation and sampling steps are embedded into an iterative refinement procedure which provides an increasingly accurate hybrid representation (Figure 7).

6.3.4. Indoor Scene Reconstruction using Primitive-driven Space Partitioning and Graph-cut

Participants: Sven Oesau, Florent Lafarge, Pierre Alliez.

In collaboration with EADS ASTRIUM

We present a method for automatic reconstruction of permanent structures of indoor scenes, such as walls, floors and ceilings, from raw point clouds acquired by laser scanners [15]. Our approach employs graph-cut to solve an inside/outside labeling of a space decomposition. To allow for an accurate reconstruction the space decomposition is aligned with permanent structures. A Hough Transform is applied for extracting the wall directions while allowing a flexible reconstruction of scenes. The graph-cut formulation takes into account data consistency through an inside/outside prediction for the cells of the space decomposition by stochastic ray casting, while favoring low geometric complexity of the model. Our experiments produces watertight reconstructed models of multi-level buildings and complex scenes (Figure 8).

6.3.5. Watertight Scenes from Urban LiDAR and Planar Surfaces

Participant: Thijs Van Lankveld.

In collaboration with Marc Van Kreveld and Remco Veltkamp



Figure 7. Reconstruction of a facade from Multi-View Stereo images using a multi-shape hybrid sampler.



Figure 8. Reconstruction of a multi-floor indoor scene from an input point cloud.

The demand for large geometric models is increasing, especially of urban environments. This has resulted in production of massive point cloud data from images or LiDAR. Visualization and further processing generally require a detailed, yet concise representation of the scene's surfaces. Related work generally either approximates the data with the risk of over-smoothing, or interpolates the data with excessive detail. Many surfaces in urban scenes can be modeled more concisely by planar approximations. We present a method that combines these polygons into a watertight model [10]. The polygon-based shape is closed with free-form meshes based on visibility information. To achieve this, we divide 3-space into inside and outside volumes by combining a constrained Delaunay tetrahedralization with a graph-cut. We compare our method with related work on several large urban LiDAR data sets. We construct similar shapes with a third fewer triangles to model the scenes. Additionally, our results are more visually pleasing and closer to a human modeler's description of urban scenes using simple boxes (Figure 10).



Figure 9. Reconstruction of watertight model from LIDAR data sets.

6.3.6. Feature-Preserving Surface Reconstruction and Simplification from Defect-Laden Point Sets

Participant: Pierre Alliez.

In collaboration with David Cohen-Steiner, Julie Digne, Mathieu Desbrun and Fernando de Goes

We introduce a robust and feature-capturing surface reconstruction and simplification method that turns an input point set into a low triangle-count simplicial complex [5]. Our approach starts with a (possibly non-manifold) simplicial complex filtered from a 3D Delaunay triangulation of the input points. This initial approximation is iteratively simplified based on an error metric that measures, through optimal transport, the distance between the input points and the current simplicial complex, both seen as mass distributions. Our approach exhibits both robustness to noise and outliers, as well as preservation of sharp features and boundaries (Figure 10). Our new feature-sensitive metric between point sets and triangle meshes can also be used as a post-processing tool that, from the smooth output of a reconstruction method, recovers sharp features and boundaries present in the initial point set.



Figure 10. Robust reconstruction through optimal transportation.

6.3.7. Splat-based Surface Reconstruction from Defect-Laden Point Sets.

Participant: Pierre Alliez.

In collaboration with Mariette Yvinec (EPI GEOMETRICA), Ricard Campos (University of Girona), Raphael Garcia (University of Girona)

We introduce a method for surface reconstruction from point sets that is able to cope with noise and outliers. First, a splat-based representation is computed from the point set. A robust local 3D RANSAC-based procedure is used to filter the point set for outliers, then a local jet surface – a low-degree surface approximation – is fitted to the inliers. Second, we extract the reconstructed surface in the form of a surface triangle mesh through Delaunay refinement (Figure 11). The Delaunay refinement meshing approach requires computing intersections between line segment queries and the surface to be meshed. In the present case, intersection queries are solved from the set of splats through a 1D RANSAC procedure. [3].



Figure 11. Splat-based reconstruction.

WIMMICS Project-Team

6. New Results

6.1. QAKiS: Question Answering wiKiframework-based System

Participants: Elena Cabrio, Julien Cojan, Amine Hallili, Serena Villata.

We worked on an extension of QAKiS, the system for open domain Question Answering over Linked Data, that allows to query DBpedia multilingual chapters. Such chapters can contain different information with respect to the English version, e.g. they provide more specificity on certain topics, or fill information gaps. QAKiS exploits the alignment between properties carried out by DBpedia contributors as a mapping from Wikipedia terms to a common ontology, to exploit information coming from DBpedia multilingual chapters (English, French and German), broadening therefore its coverage. We also worked on proposing an argumentation theory model to reason over the inconsistent information sets obtained from DBpedia multilingual chapters, and provide nevertheless a unique and motivated answer to the user.

A demo of the system is available online ⁶. The results of this research have been published in [26], [27], [54], [34].

6.2. Combining Argumentation Theory and Natural Language Processing

Participants: Elena Cabrio, Serena Villata.

With the growing use of the Social Web, an increasing number of applications for exchanging opinions with other people are becoming available online. To cut in on a debate, the participants need first to evaluate the opinions of the other users to detect whether they are in favor or against the debated issue. An automated framework to detect the relations among the arguments represented by the natural language formulation of the users opinions is therefore needed. The work in this area proposes the use of natural language techniques to identify the arguments and their relations. In particular, the textual entailment approach is adopted, i.e. a generic framework for applied semantics, where linguistic objects are mapped by means of semantic inferences at a textual level. Textual entailment is then coupled with an abstract bipolar argumentation system which allows to identify the arguments that are accepted in the considered online debate.

The same framework is also experimented to support the management of argumentative discussions in wiki-like platforms. The results of this research have been published in [16], [28], [29].

6.3. Understanding Query Behavior and Explaining Linked Data

Participants: Fabien Gandon, Rakebul Hasan.

Our main research is to understand how to assist users in querying [63] and consuming [64] Linked Data. In querying Linked Data, we help users by providing information on how a query may behave. In addition, we provide information about the behavior of similar queries executed in the past. Users can use these information for query construction and refinement. Accurately predicting query behavior is also important for workload management, query scheduling, query optimization. In consuming Linked Data, we explain why a given piece of data exists and how the data was derived. Users can use these explanations to understand and debug Linked Data. Overall, we address the followings research questions:

- i. *How to predict query behavior prior to executing the query?*
- ii. *How to explain Linked Data?*

⁶<http://qakis.org/qakis2/>

6.3.1. Predicting query behavior

To predict query behavior prior to query execution, we apply machine learning techniques on the logs of executed queries. We work with SPARQL queries and predict how long a query would take to execute. We use the frequencies and the cardinalities of SPARQL algebra operators of a query as its features. We also extract a compact set of features from the basic graph patterns belonging to the query. We achieve high accuracy ($R^2 = 0.837$) using the k-nearest neighbors regression. We also suggest similar queries from the query log using an efficient neighbors search. Users can use these suggestions to understand behaviors of similar past queries, and construct and refine their queries accordingly.

6.3.2. Explaining Linked Data

The diverse and distributed nature of Linked Data presents opportunities for large-scale data integration and reasoning over cross-domain data. In this scenario, consumers of Linked Data may need explanations for debugging or understanding ontologies. A consumer may also want a short explanation to have an overview of the reasoning. We propose to publish the explanation related metadata as Linked Data. This enables us to explain derived data in the distributed setting of Linked Data. We present the *Ratio4TA*⁷ vocabulary to describe explanation metadata and guidelines to publish these metadata as Linked Data. In addition, we summarize explanations using four measures: centrality, coherence, abstractness, and similarity. Users can specify their explanation filtering criteria - types of information they are interested in. We evaluate our summarization approach by comparing the summarized explanations generated by our approach and ground truth summarized explanations generated by humans. Our explanation summarization approach performs roughly with 60% to 70% accuracy for small summaries.

6.4. Linguistic Knowledge Representation: the Unit Graphs Formalism

Participants: Fabien Gandon, Maxime Lefrançois.

As any community of interest, linguists produce knowledge. Generic needs arise with such produced knowledge: how to represent it, how to manipulate it, how to share it, how to query it, and how to reason with it. To answer these needs is the goal of the knowledge representation (KR) domain. Existing KR formalisms such as the Semantic Web formalisms are standard solutions, and their specialization to the linguistic domain is under active development. Yet, the description logic behind the OWL formalism fails to represent how the meaning of words combine to build up the meaning of sentences. To tackle this specific problem, we introduced the new so-called Unit Graphs KR framework that is portable to existing KR standards but that introduces its own formal logic. UGs are defined over a UG-support that contains: i) a hierarchy of unit types which is strongly driven by the actantial (from action) structure of unit types, ii) a hierarchy of circumstantial symbols, and iii) a set of unit identifiers. On these foundational concepts, we defined UGs, justified the introduction of a deep-semantic representation level for the Meaning-Text Theory, we represented lexicographic definitions of lexical units, and we introduced two formal semantics: one based on UGs closure and homomorphism, and one based on model theoretic semantics. The UGs formalism has been the object of 6 publications in [42], [43], [44], [45], [46], [47].

6.4.1. Editor of Formal Lexicographic Definitions

Participants: Fabien Gandon, Alain Giboin, Romain Gugert, Maxime Lefrançois.

A prototype of a GUI of an editor of formal dictionary definitions aimed at lexicographers was developed based on the formalism of Units Graphs and on Meaning-Text Theory. The development of the GUI was preceded by the elaboration of scenarios of how users would interact with Units Graphs objects. It was followed by user tests of the GUI with actual lexicographers unfolding the scenarios. This work is reported in [46].

6.5. Access Control and Presentation for Linked Data

Participants: Luca Costabello, Fabien Gandon, Serena Villata.

⁷<http://ns.inria.fr/ratio4ta/>

PRISSMA is an *adaptive* rendering engine for Linked Data resources. PRISSMA tweaks RDF visualization to the mobile context in which the resource consumption is performed. The work in 2013 has been focused on designing the algorithm that selects the best RDF visualization according to the real, sensed context. Such *selection algorithm* finds optimal error-tolerant subgraph isomorphisms between RDF graphs using the notion of graph edit distance and is sublinear in the number of context declarations in the system. The PRISSMA selection algorithm has been implemented as an Android library, and a test campaign assessed response time and memory consumption. A proof-of-concept, PRISSMA-equipped, mobile RDF browser has been developed to test PRISSMA in a real-world application.

We proposed an extension of Shi3ld, a context-aware access control framework for the Web of Data, developed last year. In particular, we showed how the Shi3ld attribute-based authorization framework for SPARQL endpoints has been progressively converted to protect HTTP operations on RDF. We started by supporting the SPARQL 1.1 Graph Store Protocol and shifted towards a solution without SPARQL for the Linked Data Platform. The resulting authorization framework provides the same functionalities of its SPARQL-based counterpart, including the adoption of Semantic Web languages only. Moreover, a user-friendly interface allowing non expert users to create Shi3ld access policies through a GUI has been designed and developed. These results have been published in [22], [36], [35].

Luca Costabello co-supervised a six-month master student internship related to the Shi3ld project. The student, Iacopo Vagliano, from Politecnico di Torino (Italy) developed a Web application to manage Shi3ld access control policies.

6.6. Reasoning about Data Licensing in the Web of Data

Participants: Fabien Gandon, Serena Villata.

In the domain of Linked Open Data a need is emerging for developing automated frameworks able to generate the licensing terms associated to data coming from heterogeneous distributed sources. Together with Guido Governatori (NICTA, Australia) and Antonino Rotolo (University of Bologna, Italy), we proposed and evaluated a deontic logic semantics which allows to define the deontic components of the licenses, i.e., permissions, obligations, and prohibitions, and generate a composite license compliant with the licensing items of the composed different licenses. The AND-composition and OR-composition heuristics have been proposed to support the data publisher in choosing the licenses composition strategy which better suits her needs w.r.t. the data she is publishing. The approach has been evaluated using the SPINdle defeasible reasoner, where the proposed heuristics have been hard coded in the reasoner. The results of this research line have been published in [50], [38].

6.7. Semantic and Temporal Analysis of Online Communities

Participants: Catherine Faron Zucker, Fabien Gandon, Zide Meng.

This work is done in the PhD of Zide Meng in the OCKTOPUS ANR project.

Data Formalization: We use *FOAF* and *SIOC* schema to formalize a dataset from the popular question-answer site *StackOverflow* into RDF format. For some mis-matched vocabulary, we introduce *ugc* schema, which refer to user generated content. Moreover, in order to enrich the dataset, we link tag entity of our dataset to the corresponding entity in DBpedia by using cosine distance of two entities description to solve the disambiguation problem.

Analysis: After formalizing the dataset, we begin to exploit some graph mining algorithms, such as community detection algorithm, to analyse the dataset. We extract different kinds of graph from the RDF dataset, such as question-answer graph, co-answer graph, tag co-occurrence graph etc. We aim at finding useful information such as interest groups, experts and tag groups from this kind of question-answer site. By studying the state of the art of community detection algorithm, we analyse the advantage and disadvantage of different approaches, then try to introduce a better algorithm which could outperform others in this scenario.

Plan: During our analysis, we find out some difficult problems which haven't been well solved, such as question intent understanding and community evolution. We will use semantic technology, combining with social network analysis to solve this problem. In the future, we would develop an information management system for such dataset by using analysis algorithms we introduced to improve the performance of information retrieval on user generated content sites.

6.8. RDF Mining

Participant: Andrea Tettamanzi.

We started investigating an approach to RDF mining based on grammatical evolution and possibility theory: the aim is to mine large RDF graphs by automatically generating and testing OWL 2 axioms based on the known facts. This research effort brings together expertise on metaheuristics for machine learning and data mining, fuzzy logic and possibility theory for representing and handling uncertainty, and the core interests of the Wimmics team, namely, knowledge graphs and the Semantic Web.

Finally, an article describing work on the automatic design of multilayer feedforward neural networks with evolutionary algorithms carried out while still at the University of Milan, got published in [75].

6.9. Combination of Evolutionary and Semantic Web Techniques for Protein Design

Participants: David Simoncini, Andrea Tettamanzi.

Proteins are fundamental components of all living cells and are among the most studied biological molecules. They are involved in numerous diseases and being able to determine their 3D structures and interactions is essential to understand the mechanisms of cell functions. *De novo* computational protein design refers to the problem of finding a sequence of amino acids corresponding to a protein with the desired three-dimensional structure, or the desired biological function. It is a longstanding goal in computational structural biology and only a few examples of successful *de novo* computational protein designs can be found in the literature. Computational protein design has many industrial applications, such as biofuels, drug synthesis and food processing (through computational design of enzymes) or targetted drug delivery systems (through bio-nanotechnologies).

In this context, our research focuses on knowledge extraction from protein structure databases for the development of new computational protein design frameworks. Whereas most of the current methods ignore available structural information, our algorithm takes into account known profitable interactions between amino acids and uses this information to guide the energy minimization process and propose more realistic sequences of proteins.

6.10. Logical Foundations of Cognitive Agents

Participants: Andrea Tettamanzi, Serena Villata.

We carried on work on the logical foundations of cognitive agents in collaboration with Salem Benferhat of CRIL and Célia da Costa Pereira of I3S [25] and on the application of such theoretical framework to the problem of exploiting untrustworthy communication in vehicular ad-hoc networks, in collaboration with Ana L. Bazzan and Andrew Koster of the Federal University of Rio Grande do Sul in Brasil and Célia da Costa Pereira of I3S [41]; still related to the issue of trust in multi-agent systems, we took part, with Serena Villata and Célia da Costa Pereira of I3S in a joint investigation with a research team, led by Cristiano Castelfranchi, of the CNR-ISTC in Rome [19].

6.11. Requirement Engineering

Participants: Isabelle Mirbel, Zeina Azmeh.

The participation of stakeholders (and especially end-users) in requirement engineering is recognized as a key element in the development of useful and usable systems. But in practice, the involvement of end-users is often difficult to implement. Today's Web has given rise to several platforms serving the purpose of collaborative software development. Thanks to these environments, it is possible, among others, for anyone to suggest new requirements for a software under development. A lot of requirements are thus proposed by users and it becomes difficult, after a while, for the persons in charge of the software which development is hosted by the platform to understand this large set of new requirements in its entirety. An important limitation of these new approaches resides in the information overload, lacking structure and semantics.

In this context, we proposed an approach based on Semantic Web languages as well as concept lattices to identify relevant groups of stakeholders depending on their past participation. We also developed a tool supporting this approach. This work relies on Semantic Web languages and formal concept analysis. Semantic Web languages are used to annotate the data extracted from the platform and to reason about it. Formal Concept Analysis is a theory of data analysis which identifies conceptual structures among data sets. We use it to classify users as well as requirements into lattices which can then be exploited as road maps to examine new requirements. The results of this research have been published in [24].

6.12. Management of Technical and Regulatory Knowledge

Participants: Khalil Bouzidi, Michel Buffa, Catherine Faron Zucker, Nhan Le Than.

In the framework of a long-term collaboration with CSTB (Centre Scientifique et Technique du Bâtiment) on the management of technical and regulatory knowledge based on Semantic Web models and techniques, Catherine Faron Zucker and Nhan Le Than co-supervised the PhD thesis of Khalil Riad Bouzidi which has been defended on September 2013.

In the continuation of this work, Catherine Faron Zucker and Michel Buffa got involved with CSTB and three other partners on a project proposal submitted to ANR on the recommendation of technical documents in a social network of building professionals, based on the capitalization and sharing of best search practices.

6.13. Co-Construction of Community Ontologies and Corpus in a Limited Technological Environment

Participants: Olivier Corby, Papa Fary Diallo, Isabelle Mirbel.

In this thesis, we study the implementation of an online platform to build and share the collective memory of citizens in Senegal and revive stories by using a semantic layer. During the first year of this thesis, the first step has been to describe some Use Cases about the platform we would like to develop. We started to define what community means in our work which are group of people with a shared history, culture, ethnicity or interest and want to exchange or collaborate via the Web to share their knowledge of this area.

Our communities are characterized by three components: 1) a common socio-cultural interest, 2) exchange, collaboration and sharing among members and 3) use of the Internet to interact. Thanks to the use cases, we define two main types of users. A community member who is an user who participates in the construction of information and who has interactions with other users. The second type is a simple user who visits the platform for having information, he can be a tourist who want to have information about Senegalese communities activities.

With these use cases, we determine some features that the platform should have. Community members should have, among other thing, a place where they interact to collaborate. To have a "living" community, the system must notify the members of the community about new entries on their focus. Also, to have a catchy presentation, we plan to use maps with different kinds of information.

The second step has been to do a state of the art of online communities. This review allows us to find different definitions and typologies which differ from the study domain – anthropologist, sociologist, psychologist – or the objective – demographic, technological environment, members characteristic. The broadest definition takes into account our concept of community in the context of a knowledge-sharing platform is that of Porter [80]. Despite the fact that numerous typologies are proposed, none is completely consistent with our vision of community. However, the "Toronto School" proposes a category in the classification based on the knowledge transmission called "knowledge-building community" applied in the education area. We think that this type of community could be generalized in the field of socio-constructivisme development, which our communities belong to, for sharing socio-cultural knowledge.

Then, the second phase of this review has been to present the WestAfricapedia project which takes place in this thesis. The main objective is to enhance and sustain the socio-cultural heritage of Senegalese communities through a framework of sharing and co-construction of sociocultural knowledge. Thus we distinguish two main types of communities: knowledge-building community extended in the culture area and exchange information community that has sub-categories such as sports community, commercial community, etc.

6.14. Semantic Wiki

Participants: Pavel Arapov, Michel Buffa.

We worked on Semantic Web tools, more particularly on WikiNEXT, a semantic application wiki. WikiNEXT lies on the border between application wikis and modern Web based IDEs like jsbin⁸, JSFIDDLE⁹, cloud9 IDE¹⁰, etc. It has been initially created for writing documents that integrate data from external data sources of the Web of Data, such as DBpedia.org or FreeBase.com, or for writing interactive tutorials (e.g. an HTML5 tutorial, a semantic Web programming tutorial) that mix text and interactive examples in the same page. The system combines some powerful aspects from (i) wikis, such as ease of use, collaboration and openness, (ii) semantic Web/wikis such as making information processable by machines and (iii) Web-based IDEs such as instant development and code testing in a Web browser.

WikiNEXT can be used for writing documents/pages as well as for writing Web applications that manipulate semantic data, either locally or coming from the Web of Data. These applications can be created, edited or cloned in the browser and can be used for integrating data visualizations in wiki pages, for annotating content with metadata, or for any kind of processing. WikiNEXT is particularly suited for teaching Web technologies or for writing documents that integrate data from the Web of data.

6.15. Semantic Aggregation

Participant: Christophe Desclaux.

Christophe spent one year in the Wimmics team (October 2012 to October 2013) as an invited engineer funded by the BoostYourCode contest he won in 2012. The aim of the BoostYourCode contest (organized by Inria) is to offer to a junior engineer a one year full time contract to work on an innovating OpenSource project.

We worked on an RSS feed aggregation tool using Named Entities Recognition. Rador.NET¹¹ provides a specialized tool for monitoring news from various sources like RSS, twitter or facebook feeds. Rador.NET semantically increases news for a better classification for the user. We worked on document clustering, natural language processing, RDF datastores and building efficient SPARQL queries.

6.16. Semantic Mappings

Participants: Thi Hoa Hue Nguyen, Nhan Le Thanh.

⁸<http://www.jsbin.com>

⁹<http://www.jsfiddle.net>

¹⁰<http://www.cloud9ide.com>

¹¹<http://www.rador.net>

This PhD thesis is about semantic mappings with a control flow-based business workflow: an approach to develop control flow applications using knowledge-based systems.

Although software systems employed to create and execute automatically business processes have been becoming more and more available and advanced, each system is built to deal with a particular workflow type. In addition, these systems require a great deal of time and effort of expert programmers as well as the knowledge of domain experts to set up. Therefore, it is desirable to develop an alternative approach.

Our objective is to represent control flow-based business workflow patterns (CBWPs) in knowledge base by a declarative approach. We first propose an ontological model to represent Coloured Petri Nets (CPNs) with OWL DL. On this basis, we define a meta-knowledge base for CBWPs management. We then develop a graphical interface to design and simulate CBWPs. Our ongoing work is to develop a middleware prototype for mapping and using a CBWP with a user's knowledge base in order to illustrate the feasibility of our approach [49].

6.17. Emotional and Social Web

6.17.1. Modeling, Detection and Annotation of Emotional States using an Algebraic Multidimensional Vector Space

Participants: Nhan Le Thanh, Imen Tayari.

In this research work, we presents a generic solution of emotional data exchange between heterogeneous multi-modal applications. This proposal is based on a new algebraic representation of emotions and it is composed of three distinct layers: the psychological layer, the formal computational layer and the language layer. Moreover, our proposal provides powerful mathematical tools for the analysis and the processing of these emotions and it enables the exchange of the emotional states regardless to the modalities and sensors used in the detection step. The validation of the proposed solution is done with K-nearest neighbor classification algorithm for detecting and evaluating emotion from Eight-Emotion Sentics Data.

6.17.2. Social radio: a Case Studies of Social Network Services

Participants: Amosse Edouard, Nhan Le Thanh.

In this project, we carry out some case studies of social radio that is an information service on social networking. Two case studies are conducted on the topics of traffic incidents and geo-epidemiologies. These case studies allow us to study a formal model of spatiotemporal annotations on social network.

6.17.3. Participatory Mapping and Social Bookmarking

Participants: Michel Buffa, Alain Giboin.

In continuation of ISICIL, collaboration began this year between the ITCS-HSS research teams Wimmics and Tech-CICO (UTT), in association with Mnemotix and Wannago startups, in order to design a platform of participatory mapping in the field of sustainable tourism. This platform will enable the various actors in the field (tourists, tourism service providers, scientific experts of fauna, flora and geology, associations, and so on) exchange knowledge about the site and thus enhance the site attraction. This platform is called "socio-semantic" because it offers a unique combination of Semantic Web and Social Web technologies.

The article [51] details one of the planned scenarios of use of the platform and illustrates some proposed functionalities such as Webmarks (Wimmics and Mnemotix) and multiple viewpoints (Tech-CICO). The article also shows how ICT and HSS researchers will collaborate to analyze the innovative uses of the platform on the first fields of application (in Provence- Alpes-Côte d'Azur Region).

6.17.4. Modeling Team Processes

Participants: Pierre Robillard, Isabelle Mirbel, Zeina Azmeh, Alain Giboin, Mathieu Lavallée.

Recent studies outline the importance of software development teams' interactions, suggesting that poor team dynamics can lead to poor software. The relationship between "soft" issues like team dynamics and "hard" issues like software quality is difficult to observe, however. To bridge the gap between these two kinds of issues, and to help development teams prevent quality issues through the planning of relevant team activities, we worked on an assessment method of the quality of team dynamics based on a taxonomy of episodes of interactions encountered in software development teams [83] – the CoDyMA (Collaborative Dynamics Measurement and Analysis) method. We proposed an analysis procedure of episodes based on the Formal Concept Analysis (FCA) approach. This procedure uses as input the data (namely the accounts of face-to-face interactions) reported by the developers in their activity diary. The entries are coded in terms of interaction episodes and artifact types to produce a FCA lattice. The observed lattice is compared to a prescribed lattice, and adjustments can be proposed to the team if necessary. The procedure was applied to data from a case study. This work is described in a paper submitted for publication.

6.17.5. Modeling Users and Groups of Users

Participants: Isabelle Mirbel, Zeina Azmeh, Alain Giboin.

6.17.5.1. Emphasizing Dysfunctional Group Dynamics in Collaboration Personas: Specification of an Approach

Comparing Collaboration Personas and Individual Personas for the design and evaluation of collaboration software, Judge, Matthews, and Whittaker [79] found that practitioners preferred collaboration personas, but required that the method put more emphasis on problematic or dysfunctional group dynamics. Because Judge et al. only outlined a possible approach to meet this requirement, we decided to contribute to the specification of the approach. In [37] we report the first steps of this specification work.

6.17.5.2. Using Formal Concept Analysis to elicit Personas

Personas are built from a clustering of behavioral variables common to a set of users. Behavioral variables are ways in which users behavior differ (e.g., goals and attitudes); it is important to elicit them because they have an impact on the system to be designed. Today, the clustering is mainly performed manually. To automate it, we started this year to explore the use of Formal Concept Analysis tools.

6.17.6. Modeling Multimodal Grounding Processes in Design Teams

Participants: Aurore Defays, Alain Giboin.

Grounding is the process used by participants to a collective activity to coordinate both the content and process of their communication to be successful [71]. Grounding is also defined as the process of elaborating and maintaining the Common Ground (i.e., mutual knowledge, mutual beliefs, and mutual assumptions) necessary to participants' mutual understanding [72]. So far, grounding has been studied mainly from a unimodal point of view, i.e., from the point of view of the verbal modality (oral or written). Some authors have begun to study grounding from a bimodal viewpoint; for example [78] have studied the use of verbal and gestural modalities necessary to ensure mutual understanding in interactions between Japanese airline pilots and an American flight instructor. In the context of her PhD thesis in Ergonomics applied to architectural design digital tools, Aurore Defays extended the study of grounding to actual multimodality (with n modality: oral, written, gestures, gazes, etc.).

With Aurore Defays, we focused this year on improving the methodology of analysis of multimodal grounding proposed in [74]. To do this, we relied on the data of an existing study by Defays on remote collaboration between dyads and triads of architects interacting through a collaborative digital studio (the Distributed Collaborative Digital Studio, DSDC). Our initial research question was: Is a multimodal shared representation preferable to a unimodal representation to collaborate effectively? Analyzing the data, this question was gradually transformed into: Which modalities are relevant to build the common ground necessary for a particular type of collaboration to succeed?

6.17.7. The "Design Thinking" Toolset: Application to Discovery Hub

Participants: Gessica Puri, Alain Giboin, Nicolas Marie, Damien Legrand.

Last year was developed a "design thinking" toolset (including a framework) for helping developers think in terms of a user's point of view when they design and evaluate link visualization and manipulation applications such as graph visualization applications [81]. The toolset was used this year to perform a qualitative evaluation of Discovery Hub, so contributing to the development of a new version of the discovery engine.

The ShowCaseMachine project led by Damien Legrand won the 11th Challenge *Jeune Pousses* at Telecom Valley in Sophia Antipolis.

6.18. Graph-based Knowledge Representation

6.18.1. SPARQL Based Pretty Printing Language

Participant: Olivier Corby.

We have designed SPARQL Template, a pretty-printing rule language for RDF graphs. It enables to pretty print RDF graphs representing Abstract Syntax Trees of languages such as SPIN or OWL RDF syntax. We have implemented a pretty printing engine that interprets SPARQL Template.

An example of template for a OWL "someValuesFrom" statement is shown below. The SPARQL 1.1 "where" part specifies the conditions to apply the rule on a focus node "?in". The template part specifies the result of the pretty print of the focus node. Variables in the template part are recursively replaced by the result of their pretty print.

```
template {
  "someValuesFrom(" ?p " " ?c ") "
}
where {
  ?in a owl:Restriction ;
  owl:onProperty ?p ;
  owl:someValuesFrom ?c
}
```

We have introduced named templates that are called explicitly using a "kg:template" extension function.

The pretty printing language and engine have been validated on five RDF AST¹²: SPIN, OWL 2, SQL, Turtle and a mockup of mathematical expressions pretty printed into Latex. The SPIN pretty printer is used in the PhD Thesis of Oumy Seye on "Rules for the Web of Data" and the SQL pretty printer is used in the PhD Thesis of Corentin Follenfant on "Usage semantics of analytics and Business Intelligence tools".

6.18.2. Federated Semantic Data Query

Participants: Olivier Corby, Alban Gaignard.

Another activity of the team addresses the data explosion challenges faced in e-Science. Semantic Web technologies are well adopted to represent the knowledge associated to both e-Science data and processing tools. A PhD thesis [76], addressing the distributed knowledge production and sharing in collaborative e-Science platforms, has successfully been defended this year. Moreover, we have been participating in the organization of the second edition of the CrEDIBLE workshop¹³, gathering international experts to discuss the challenges of federating distributed biomedical imaging data and knowledge.

In this area, the main scientific results are (i) a software architecture for transparently querying multiple data sources through the SPARQL language [73], (ii) a set of querying strategies and optimizations dedicated to limit the cost of distributed query processing, while still considering enough expressivity (full SPARQL 1.1 support, including named graphs, property path expressions, optional, aggregates, etc.).

¹²<ftp://ftp-sop.inria.fr/wimmics/soft/pprint>

¹³<http://credible.i3s.unice.fr>

Performance-oriented experiments have been conducted on the Grid'5000 distributed computing infrastructure to compare our approach with state-of-the-art engines such as FedX [85], Splendid [77], or DARQ [82]. Experiments, based on the FedBench benchmark [84] show performances between DARQ, Splendid, and FedX, while still high expressivity.

Since distributed query processing lead to complex and costly processes, we started to collect provenance information which opens interesting perspectives towards enhanced trust and reproducibility in Linked Data querying and reasoning.

These distributed query processing strategies have been implemented and integrated into Corese through two main components, namely a data source federator, and a data source endpoint. A prototype Web application has also been developed to demonstrate our approach. End-users can configure and launch distributed SPARQL querying and finally visualize SPARQL results and their associated provenance.

6.18.3. Rules for the Web of Data

Participants: Olivier Corby, Catherine Faron Zucker, Oumy Seye.

This work takes place in the PhD Thesis of Oumy Seye.

The objective of this year is to foster knowledge reuse on the Web based on the principles of Linked Data. Our approach is to consider rule bases like data sources that can be published, shared and queried as Linked Data, thus enabling the selection and reuse of relevant and useful shared rules in any particular context or application. We propose to select rules by querying either metadata annotating rules, rules content or both. To make rules content queryable, we use RDF representations of SPARQL rules with the SPIN format ¹⁴.

This idea joins the principles of the Semantic Web that encourages the sharing and reuse of knowledge. We used the SPIN syntax (which allows the representation of a SPARQL query in RDF) obtained with the SPIN pretty printer of Corese. We have subsequently been able to select rules of interest with Corese. The proposal enables to search rules based on their content. This allows us to help users extract relevant set of rules for their data, and thus leverage more easily shared rules. This idea can be used to build a search engine for rules on the Web or a tool for automatically connect rules with semantic data.

In the remainder of this work, we will focus on updating harvested rules. A poster on this work was presented for the GLC pole day July 8, and at the summer school ESWC September 2.

6.18.4. Semantic Web and Business Intelligence

Participants: Corentin Follenfant, Olivier Corby, Fabien Gandon.

This PhD Thesis is done with a CIFRE industrial grant from SAP Research.

The bilateral contract with SAP aims at converging Semantic Web and Business Intelligence through a framework applying the read/write Web principles to the business knowledge carried within Business Intelligence reports. These reports often provide a dynamic view upon numerical data from various enterprise sources, mainly relational databases. Reports are authored with a complex process that can be reduced to writing, directly or through different layers of user interfaces, SQL queries that will query the sources and feed the dynamic reports. In order to simplify the query authoring process, complementary approaches are envisioned.

Our approach proposes to model the queries as knowledge through their abstract syntax trees (ASTs) with Semantic Web tools, query and manipulate them through appropriate standards, respectively RDF/S and SPARQL. Indeed RDF enables us to model the actual structure of the ASTs by integrating the knowledge related to syntax and semantics of the SQL queries: types can be captured with XML Schema Datatypes, while more specific business knowledge can also be designed according to the source business models and annotate various entities referenced within the SQL queries. Regarding the query and manipulation part, a library of SPARQL queries was designed to perform generic AST manipulation (generic from a DSL perspective), and is usable to search, extract, edit, prune or graft parts of RDF-modelled ASTs.

¹⁴<http://www.w3.org/Submission/spin-overview/>

While this year was mostly dedicated to manuscript writing, additional experiments were run to demonstrate the validity of our model: a large set of ANSI SQL queries generated with a TPC-DS benchmark was converted to its RDF representation. Inversely, a generic pretty printer system developed into the Corese engine was validated by the internship of Abdoul Macina who developed a set of rules to have the pretty printer turn RDF-modelled SQL queries back to their concrete syntactic form. This enables iterative query design by leveraging AST patterns rather than manually editing brute syntax.

ZENITH Project-Team

6. New Results

6.1. Big Data Integration

6.1.1. Probabilistic Data Integration

Participants: Reza Akbarinia, Naser Ayat, Patrick Valduriez.

Data uncertainty in scientific applications can be due to many different reasons: incomplete knowledge of the underlying system, inexact model parameters, inaccurate representation of initial boundary conditions, inaccuracy in equipments, error in data entry, etc.

An important problem that arises in big data integration is that of Entity Resolution (ER). ER is the process of identifying tuples that represent the same real-world entity. The problem of *entity resolution over probabilistic data* (which we call ERPD) arises in many distributed application domains that have to deal with probabilistic data, ranging from sensor databases to scientific data management. The ERPD problem can be formally defined as follows. Let e be an uncertain entity represented by multiple possible alternatives, i.e. tuples, each with a membership probability. Let D be an uncertain database composed of a set of tuples each associated with a membership probability. Then, given e , D , and a similarity function F , the problem is to find the entity-tuple pair (t, t_i) (where $t \in e, t_i \in D$) such that (t, t_i) has the highest cumulative probability to be the most similar in all possible worlds. This entity-tuple pair is called the *most probable match pair* of e and D , denoted by MPMP(e, D).

Many real-life applications produce uncertain data distributed among a number of databases. Dealing with the ERPD problem for distributed data is quite important for such applications. A straightforward approach for answering distributed ERPD queries is to ask all distributed nodes to send their databases to a central node that deals with the problem of ER by using one of the existing centralized solutions. However, this approach is very expensive and does not scale well neither in the size of databases, nor in the number of nodes.

In [20], we proposed FD (Fully Distributed), a decentralized algorithm for dealing with the ERPD problem over distributed data, with the goal of minimizing bandwidth usage and reducing processing time. It has the following salient features. First, it uses the novel concepts of *Potential* and *essential-set* to prune data at local nodes. This leads to a significant reduction of bandwidth usage compared to the baseline approaches. Second, its execution is completely distributed and does not depend on the existence of certain nodes. We validated FD through implementation over a 75-node cluster and simulation using both synthetic and real-world data. The results show very good performance, in terms of bandwidth usage and response time.

6.1.2. Open Data Integration

Participants: Emmanuel Castanier, Patrick Valduriez.

Working with open data sources can yield high value information but raises major problems in terms of metadata extraction, data source integration and visualization. For instance, Data Publica provides more than 12 000 files of public data. However, even though data formats become richer and richer in terms of semantics and expressivity (e.g. RDF), most data producers do not use them much in practice, because they require too much upfront work, and keep using simpler tools like Excel. Unfortunately, no integration tool is able to deal in an effective way with spreadsheets. Only few initiatives (OpenII and Google Refine) deal with Excel files. However, their importers are very simple and make some strict restrictions over the input spread-sheets.

In [31], we describe a demonstration of WebSmatch, a flexible environment for Web data integration. WebSmatch supports the full process of importing, refining and integrating data sources and uses third party tools for high quality visualization. We use a typical scenario of public data integration which involves problems not solved by current tools: poorly structured input data sources (XLS files) and rich visualization of integrated data.

6.1.3. Pricing Integrated Data

Participant: Patrick Valduriez.

Data is a modern commodity, being bought and sold. Electronic data market places and independent vendors integrate data and organize their online distribution. Yet the pricing models in use either focus on the usage of computing resources, or are proprietary, opaque, most likely ad hoc, and not conducive of a healthy commodity market dynamics. In [39], we propose a generic data pricing model that is based on minimal provenance, i.e. minimal sets of tuples contributing to the result of a query. We show that the proposed model fulfills desirable properties such as contribution monotonicity, bounded-price and contribution arbitrage-freedom. We present a baseline algorithm to compute the exact price of a query based on our pricing model. We show that the problem is NP-hard. We therefore devise, present and compare several heuristics. We conduct a comprehensive experimental study to show their effectiveness and efficiency.

In most data markets, prices are prescribed and accuracy is determined by the data. Instead, we consider a model in which accuracy can be traded for discounted prices: “what you pay for is what you get”. The data market model consists of data consumers, data providers and data market owners. The data market owners are brokers between the data providers and data consumers. A data consumer proposes a price for the data that she requests. If the price is less than the price set by the data provider, then she gets an approximate value. The data market owners negotiate the pricing schemes with the data providers. They implement these schemes for the computation of the discounted approximate values. In [38], we propose a theoretical and practical pricing framework with its algorithms for the above mechanism. In this framework, the value published is randomly determined from a probability distribution. The distribution is computed such that its distance to the actual value is commensurate to the discount. The published value comes with a guarantee on the probability to be the exact value. The probability is also commensurate to the discount. We present and formalize the principles that a healthy data market should meet for such a transaction. We define two ancillary functions and describe the algorithms that compute the approximate value from the proposed price using these functions. We prove that the functions and the algorithm meet the required principles.

6.2. Distributed Indexing and Searching

6.2.1. P2P Search and Recommendation

Participants: Esther Pacitti, Maximilien Servajean.

In crossdiscipline domains, users belonging to different communities produce various scientific material that they own, share, or endorse. In that context, we are interested in querying and recommending scientific material in the form of documents. Such documents cover various topics such as models for plant phenotyping, statistics on specific kinds of plants, or biological experiments.

In [40], we investigate profile diversity, a novel idea in searching scientific documents. Combining keyword relevance with popularity in a scoring function has been the subject of different forms of social relevance. On the other hand, content diversity has been thoroughly studied in search and advertising, database queries, and recommendations.

We introduce profile diversity for scientific document search as a complement to traditional content diversity. Profile diversity combines the discipline and communities to which a user belongs. We propose an adaptation of Fagin’s threshold-based algorithms to return the most relevant and most popular documents that satisfy content and profile diversities. To validate our scoring function, DivRSci, we ran experiments that use two benchmarks: a realistic benchmark with scientists and TREC’09. We show that DivRSci presents the best compromise between all requirements we have identified. DivRSci also shows to be the best generating list of inter-disciplinary and inter-community documents. Finally, it yields very good gains (by a factor of 6), suited for profile diversification

6.2.2. Spatial Queries in Wireless Data Broadcasting

Participant: Patrick Valduriez.

The main requirements for spatial query processing via mobile terminals include rapid and accurate searching and low energy consumption. Most location-based services (LBSs) are provided using an on-demand method, which is suitable for light-loaded systems where contention for wireless channels and server processing is not severe. However, as the number of users of SBSs increases, performance deteriorates rapidly since the servers' capability to process queries is limited. Furthermore, the response time of a query may significantly increase with the concentration of users' queries in a server at the same time. That is because the server has to check the locations of users and potential objects for the final result and then individually send answers to clients via a point-to-point channel. At this time, an inefficient structure of spatial index and searching algorithm may incur an extremely large access latency.

To address this problem, we propose in [27] the Hierarchical Grid Index (HGI), which provides a light-weight sequential location-based index structure for efficient SBSs. We minimize the index size through the use of hierarchical location-based identifications. And we support efficient query processing in broadcasting environments through sequential data transfer and search based on the object locations. We also propose Top-Down Search and Reduction-Counter Search algorithms for efficient searching and query processing. HGI has a simple structure through elimination of replication pointers and is therefore suitable for broadcasting environments with one-dimensional characteristics, thus enabling rapid and accurate spatial search by reducing redundant data. Our performance evaluation shows that our proposed index and algorithms are accurate and fast and support efficient spatial query processing.

6.3. Big Data Analysis

6.3.1. Big Data Analysis using Algebraic Workflows

Participants: Jonas Dias, Patrick Valduriez.

Analyzing big data requires the support of dataflows with many activities to extract and explore relevant information from the data. Recent approaches such as Pig Latin propose a high-level language to model such dataflows. However, the dataflow execution is typically delegated to a MapReduce implementation such as Hadoop, which does not follow an algebraic approach, thus it cannot take advantage of the optimization opportunities of PigLatin algebra.

In [35], we propose an approach for big data analysis based on algebraic workflows, which yields optimization and parallel execution of activities and supports user steering using provenance queries. We illustrate how a big data processing dataflow can be modeled using the algebra. Through an experimental evaluation using real datasets and the execution of the dataflow with Chiron, an engine that supports our algebra, we show that our approach yields performance gains of up to 19.6% using algebraic optimizations in the dataflow and up to 39% of time saved on a user steering scenario.

This work was done in the context of the CNPq-Inria Hoscarr project and FAPERJ-Inria P2Pcloud project .

6.3.2. Big Data Partitioning

Participants: Reza Akbarinia, Miguel Liroz, Esther Pacitti, Patrick Valduriez.

The amount of data that is captured or generated by modern computing devices has augmented exponentially over the last years. For processing this *big data*, parallel computing has been a major solution in both industry and research. This is why, the MapReduce framework, which provides automatic distribution parallelization and fault-tolerance in a transparent way over lowcost machines, has become one of the standards in big data analysis.

For processing a big dataset over a cluster of nodes, one main step is data partitioning (or fragmentation) to divide the dataset to the nodes. In our team, we study the problem of data partitioning in two different contexts: (1) in scientific databases that are continuously growing and (2) in the MapReduce framework. In both cases, we propose automatic approaches, which are performed transparently to the users, in order to free them from the burden of complex partitioning.

In [25], we consider applications with very large databases, where data items are continuously appended. Thus, the development of efficient data partitioning is one of the main requirements to yield good performance. In particular, this problem is harder in the case of some scientific databases, such as astronomical catalogs. The complexity of the schema limits the applicability of traditional automatic approaches based on the basic partitioning techniques. The high dynamicity makes the usage of graph-based approaches impractical, as they require to consider the whole dataset in order to come up with a good partitioning scheme. In our work, we propose *DynPart* and *DynPartGroup*, two dynamic partitioning algorithms for continuously growing databases [25]. These algorithms efficiently adapt the data partitioning to the arrival of new data elements by taking into account the affinity of new data with queries and fragments. In contrast to existing static approaches, our approach offers constant execution time, no matter the size of the database, while obtaining very good partitioning efficiency. We validate our solution through experimentation over real-world data; the results show its effectiveness.

In [37] and [43], we address the problem of high data transfers in MapReduce, and propose a technique that repartitions tuples of the input datasets. Our technique optimizes the distribution of key-values over mappers, and increases the data locality in reduce tasks. It captures the relationships between input tuples and intermediate keys by monitoring the execution of a set of MapReduce jobs which are representative of the workload. Then, based on those relationships, it assigns input tuples to the appropriate chunks. With this data repartitioning and a smart scheduling of reducer tasks, our approach significantly contributes to the reduction of transferred data between mappers and reducers in job executions. We evaluate our approach through experimentation in a Hadoop deployment on top of Grid5000 using standard benchmarks. The results show high reduction in data transfer during the shuffle phase compared to Native Hadoop.

6.4. Data Stream Mining

6.4.1. Mining Uncertain Data Streams

Participants: Reza Akbarinia, Florent Masegla.

Discovering Probabilistic Frequent Itemsets (PFI) is very challenging since algorithms designed for deterministic data are not applicable in probabilistic data. The problem is even more difficult for probabilistic data streams where massive frequent updates need to be taken into account while respecting data stream constraints. In [28], we propose FEMP (Fast and Exact Mining of Probabilistic data streams), the first solution for exact PFI mining in data streams with sliding windows. FEMP allows updating the frequentness probability of an itemset whenever a transaction is added or removed from the observation window. Using these update operations, we are able to extract PFI in sliding windows with very low response times. Furthermore, our method is exact, meaning that we are able to discover the exact probabilistic frequentness distribution function for any monitored itemset, at any time. We implemented FEMP and conducted an extensive experimental evaluation over synthetic and real-world data sets; the results illustrate its very good performance.

6.4.2. Itemset Mining over Tuple-Evolving Data Streams

Participant: Florent Masegla.

In many data streaming applications today, tuples inside the streams may get revised over time. This type of data stream brings new issues and challenges to the data mining tasks. In [42] we present a theoretical analysis for mining frequent itemsets from sliding windows over such data. We define conditions that determine whether an infrequent itemset will become frequent when some existing tuples inside the streams have been updated. We design simple but effective structures for managing both the evolving tuples and the candidate frequent itemsets. Moreover, we provide a novel verification method that efficiently computes the counts of candidate itemsets. Experiments on real-world datasets show the efficiency and effectiveness of our proposed method.

6.5. Scalable Data Analysis

6.5.1. Scalable Mining of Small Visual Objects

Participants: Pierre Letessier, Julien Champ, Alexis Joly.

Automatically linking multimedia documents that contain one or several instances of the same visual object has many applications including: salient events detection, relevant patterns discovery in scientific data or simply web browsing through hyper-visual links. Whereas efficient methods now exist for searching rigid objects in large collections, discovering them from scratch is still challenging in terms of scalability, particularly when the targeted objects are small compared to the whole image. In a previous work, we revisited formally the problem of mining or discovering such objects, and then generalized two kinds of existing methods for probing candidate object seeds: weighted adaptive sampling and hashing based methods. This year, we continued working on the subject by improving our high-dimensional data hashing strategy, that works first at the visual level, and then at the geometric level. We conducted new experiments on a dedicated evaluation dataset ⁵ and we did show that our the recall or our approach definitely outperforms the reference method [46].

Based on this contribution, we then address the problem of suggesting object-based visual queries in a multimedia search engine [22], [36]. State-of-the-art visual search systems are usually based on the query-by-window paradigm: a user selects any image region containing an object of interest and the system returns a ranked list of images that are likely to contain other instances of the query object. User's perception of these tools is however affected by the fact that many submitted queries actually return nothing or only junk results (complex non-rigid objects, higher-level visual concepts, etc.). In [22], we addressed the problem of suggesting only the object's queries that actually contain relevant matches in the dataset. This requires to first discover accurate object's clusters in the dataset (as an offline process); and then to select the most relevant objects according to user's intent (as an on-line process). We therefore introduce a new object's instances clustering framework based on a bipartite shared-neighbours clustering algorithm that is used to gather object's seeds discovered by our visual mining method. Shared nearest neighbours methods were not studied beforehand in the case of bipartite graphs and never used in the context of object discovery. Experiments show that this new method outperforms state-of-the-art object mining and retrieval results on the Oxford Building dataset. We finally describe two real-word object-based visual query suggestion scenarios using the proposed framework and show examples of suggested object queries. A demo was presented at ACM Multimedia 2013 [36].

This method was finally integrated within a visual-based media event detection system in the scope of a French project called the Transmedia Observatory [33]. It allows the automatic discovery of the most circulated images across the main news media (news websites, press agencies, TV news and newspapers). The main originality of the detection is to rely on the transmedia contextual information to denoise the raw visual detections and consequently focus on the most salient trans-media events.

6.5.2. *Rare Events Identification for Large-Scale Applications*

Participant: Florent Masegla.

While significant work in data mining has been dedicated to the detection of single outliers in the data, less research has approached the problem of isolating a group of outliers, i.e. rare events representing micro-clusters of less – or significantly less – than 1% of the whole dataset. This research issue is critical for example in medical applications. The problem is difficult to handle as it lies at the frontier between outlier detection and clustering and distinguishes by a clear challenge to avoid missing true positives. In [41], we address this challenge and propose a novel two-stage framework, based on a backward approach, to isolate abnormal groups of events in large datasets. The key of our backward approach is to first identify the core of the dense regions and then gradually augment them based on a density-driven condition. The framework outputs a small subset of the dataset containing both rare events and outliers. We tested our framework on a biomedical application to find micro-clusters of pathological cells. The comparison against two common clustering (DBSCAN) and outlier detection (LOF) algorithms show that our approach is a very efficient alternative to the detection of rare events – generally a recall of 100% and a higher precision, positively correlated with the size of the rare event – while also providing a $\mathcal{O}(N)$ solution to the existing algorithms dominated by a $\mathcal{O}(N^2)$ complexity.

6.5.3. *Large-scale content-based plants identification from social image data*

Participants: Hervé Goëau, Alexis Joly, Julien Champ, Saloua Litayem.

⁵<http://www-sop.inria.fr/members/Alexis.Joly/BelgaLogos/FlickrBelgaLogos.html>

Speeding up the collection and integration of raw botanical observation data is a crucial step towards a sustainable development of agriculture and the conservation of biodiversity. Initiated in the context of a citizen sciences project in collaboration with the botanists of the AMAP UMR team and Tela Botanica social network, the overall contribution of this work [23] is an innovative collaborative workflow focused on image-based plant identification as a mean to enlist new contributors and facilitate access to botanical data. Since 2010, hundreds of thousands of geo-tagged and dated plant photographs were collected and revised by hundreds of novice, amateur and expert botanists of a specialized social network. An image-based identification tool - available as both a web and a mobile application - is synchronized with that growing data and allows any user to query or enrich the system with new observations. Extensive experiments of the visual search engine as well as system-oriented and user-oriented evaluations of the application did show that it is very helpful to determine a plant among hundreds or thousands of species [23]. As a concrete result, more than 80K people in about 150 countries did download the iPhone end point of the application [32].

From a data management and data analysis perspective, our main contribution concerns the scalability of the system. At the time of writing, the content-based search engine actually works on 120K images covering more than 5000 species (which already makes it the largest identification tool built anytime). The resulting training dataset contains several hundreds of millions feature vectors, each with several hundreds of float attributes (i.e. high-dimensional feature vectors describing the visual content). At query time, thousands of such feature vectors are extracted from the query pictures and have to be searched online in the training set to find the most similar pictures. The underlying search of approximate nearest neighbors is speed-up thanks to a data-dependent high-dimensional hashing framework based on Random Maximum Margin Hashing (RMMH), a new hash function family that we introduced in 2011. RMMH is used for both compressing the original feature vectors into compact binary hash codes and for partitioning the data into a well balanced hash table. Search is then performed through adaptive multi-probe accesses in the hash table and a top-k search refinement step on the full binary hash codes. Last improvements brought in 2013 include a multi-threaded version of the search, the use of a probabilistic asymmetric distance instead of the Hamming distance and the integration of a query optimization training stage in the compressed feature space instead of the original space. A beta version of Pl@ntNet visual search engine based on these new contributions is currently being tested and is about 8 times faster than the one used in production.

Besides scalability and efficiency, we also did work on improving the identification performances of the system [29]. We notably improved the quality of the top-K returned images by weighting each match according to its Hamming distance to the query rather than using a simple vote. We then improved the multi-cue fusion strategy by indexing separately each type of visual features rather than concatenating them in an early phase. We finally did train the optimal selection of features for each of the considered plant organ (flower, leaf, bark, fruit). Beyond the use of the visual content itself, we explored the usefulness of associated metadata and we did prove that some of them like the date can improve the identification performances (contrary to the geo-coordinates that surprisingly degraded the results). Overall, as a result of our participation to ImageCLEF plant identification benchmark [34], we obtained the second best run among 12 international groups and a total of 33 submitted runs.

COPRIN Project-Team

6. New Results

6.1. Robotics

6.1.1. Cable-driven parallel robots (CDPR)

6.1.1.1. Analysis of Cable-driven parallel robots

Participants: Laurent Blanchet, Jean-Pierre Merlet [correspondant], Yves Papegay, Rémy Ramadour.

We are still investigating the extremely complex analysis of the kinematics [24] of CDPRs assuming either rigid [21] [20], elastic or sagging cables.

We have also started an analysis of *cable configuration* of redundantly actuated CDPRs for control purposes. Indeed we have shown that for robot with rigid cables it is impossible to have, in a given pose, more than 6 cables in tension simultaneously: the set of cables under tension is called the cable configuration. However at a pose there may be different sextuplets of under tension cables that satisfy the kinematico-static equations. Each of these sextuplets exhibits different performances (e.g. maximal tension in the cables or sensitivity of the positioning to errors in the cable lengths). Hence it may be interesting for control purposes to select one of the sextuplet that is optimal with respect to a performance criteria and to enforce this configuration by letting *voluntary* the cables that are not in the sextuplet being slack (i.e. adjusting their lengths to be larger than the one required for the pose).

We have generalized this approach for a trajectory of a 4 cables CDPR with all cables attached to the same point of the platform. In that case only up to 3 cables may be under tension at the same time. We have designed an algorithm that determine the optimal cable configuration on the whole trajectory.

Simultaneously we have addressed part of an ambitious goal: a full simulation tool for CDPR. We assume a high level motion planning loop that calculate a motion order every Δt_1 second and send this command to an inner motor control loop that execute it by sending a command to the motor every Δt_2 second. Then we have a continuous time model of the motor that determine its velocity. The whole purpose is to calculate the pose of the platform together with the tensions in the cables. This simulation is extremely demanding and cannot be performed with classical software because of the changes in the cable configuration that have to be detected for determining the platform pose and cable tensions. We have succeeded for CDPR with rigid and elastic cables, furthermore introducing random errors in the cable length measurements. This tool has allowed us to show that cable tensions are very sensitive: for example a high level loop that is designed to minimize $\sum \tau_j^2$, where τ are the cable tensions, exhibits large difference with the objective as soon as discrete time-control is taken into account.

6.1.1.2. Certified Calibration of a Cable-Driven Robot Using Interval Contractor Programming

Participants: Julien Alexandre Dit Sandretto, David Daney, Gilles Trombettoni.

An interval based approach is proposed to rigorously identify the model parameters of a parallel cable-driven robot. The studied manipulator follows a parallel architecture having 8 cables to control the 6 DOFs of its mobile platform. This robot is complex to model, mainly due to the cable behavior. To simplify it, some hypotheses on cable properties (no mass and no elasticity) are done. An interval approach can take into account the maximal error between this model and the real one. This allows us to work with a simplified although guaranteed interval model. In addition, a specific interval operator makes it possible to manage outliers. A complete experiment validates our method for robot parameter certified identification and leads to interesting observations [9], [16], [15].

6.1.1.3. Tool for Agencement Analysis and Synthesis of CDPRs

Participants: Laurent Blanchet, Jean-Pierre Merlet [correspondant].

In the frame of FP7 project CABLEBOT, we are developing a methodology to analyze or synthesize a Cable Driven Parallel Robots configuration i.e. either to determine the performances of a given CDPR (e.g. maximal wire tensions over a given workspace) or, being given a list of requirements, to determine what what are **all** possible CDPR geometries that are guaranteed to satisfy the requirements. This tool relies heavily on our analysis of the CDPRs and on interval analysis.

To illustrate this approach we have developed a software that can be used to illustrate the workings/operating procedure of interval analysis through a 3D visualization. This software sets up a scenario of a CDPR in a warehouse and computes in real time its workspace under different constraints.

6.1.1.4. *Visual-servoing of a parallel cable-driven robot*

Participants: Rémy Ramadour, Jean-Pierre Merlet [correspondant], François Chaumette [correspondant].

MARIONET-ASSIST is a parallel cable-driven robot designed to move through large rooms in order to provide services such as walking-aid, lifting people or manipulating heavy loads. In order to experiment, a full-scaled flat with a crane robot has been built. Adding one or several low-cost cameras (the cost being here a fundamental constraint), visual-servoing control is used to provide a whole new set of useful services such as grasping objects in order to bring them to the end-user (if they are too heavy, too far, high or low), or cleaning the table after lunch. Using a parallel crane robot, we are able to cover a large workspace, the vision-control allowing us to obtain the precision required by the manipulation of daily-life objects. The collaborative implementation of the vision and the kinematic control of the robot gives us a way to make best use of the advantages of both parts, while overcoming their respective drawbacks.

This project is supported by the large-scale initiative PAL.

Experimentation showed that we are able to provide a much better accuracy and repeatability using visual-servoing. However, the velocity of the process is slowed because of several encountered problems :

- when there are changes in the distribution of tension between the wires, oscillations are occurring on the end-effector, affecting the movement of the camera in such a way that we can not rely on the measurements
- the methods used to first detect the object are not satisfactory. Also, the actual segmentation is not robust to luminance changes, the target may thus be lost during the process.

In order to overcome the first problem, we are working on an algorithm able to determinate the best sequence of configurations (distribution of tension) : we can avoid singularities and provide a more stable trajectory. The second problem has yet to be solved : we are at the moment looking into several methods, using for example k-nearest neighbors algorithms with different color spaces, gradient-based information and morphological preprocessing.

Finally, we experimented our device with others technologies developed within the context of PAL, in a full-scaled apartment located in Nancy (Loria-Inria).

6.1.2. *Assistance robotics*

This is now the core of our activity and our work on CDPR is deeply connected to this field as they are an efficient solution for mobility assistance, a high priority for the elderly, helpers and medical community. We have presented our vision of assistance robotics in several occasions [22], [23], [19].

6.1.2.1. *Assessment of elderly frailty*

Participants: Karim Bakal, Jean-Pierre Merlet.

The assessment of elderly frailty is a difficult concept because it involves the physical capacities of a person and its environment (health-care services, families, funds...). To evaluate the physical abilities, biomechanics tests can be underwent on the upper limb, lower limb or the whole body. In particularly, the motricity of the upper limb can be measured in terms of range of motion, velocity, acceleration or forces.

To analyze the velocity of the loads in the upper limb, a polytope interpretation is used. Currently the force polytope at the hand is calculated from the torques τ measured at each joint (shoulder, elbow and wrist) by a dynamometer (Biodex III, Biodex Medical Systems). But because of the redundancy of the upper limb (7 degrees of freedom), the dynamic equation ($\tau = \mathbf{J}^T F$) is difficult to solve. To find the minimal and maximal forces F that can be exerted at the hand from the measured torques, we may use the jacobian pseudo-inverse with the method of Chiacchio but this method is not well suited to manage the large uncertainties in the measurements. In the a reverse approach, the force at the hand will be measured by a 6-axis load sensor and the minimal and maximal joint torques will be computed by using interval analysis and compared with the measurements of the Biodex.

Moreover this analysis of the force capacities in the upper limb need to be connected to the daily activities or usual motion test monitored by the medical services. Therefore, a review of tests and questionnaires regularly used to measure the physical capacities has been performed. This review gather the type of mark, the exercises and the used sensors that can be employed in future experimentation. Also, this review will be discussed with medical staff to highlight relevant activities.

6.1.2.2. *Walking analysis*

Participants: Claire Dune, Ting Wang, Jean-Pierre Merlet [correspondant].

In the period 2009-2013 we have conducted in collaboration with Nice hospital a large experiment involving 54 subjects (30 elderly and 24 young adults) for determining walking pattern of elderly people using our instrumented walker ANG-light. We have started the processing of this large amount of data we some interesting results [25]:

- a classical walking test is the 10 meter walking test: the subject is asked to perform a 10m straight line trajectory and the result is the total time. Such test may have large consequences as it is used to determine the autonomy level and the resulting financial aid. Our test has surprisingly shown that when using a walker elderly people are usually faster than young adults
- on the other hand the maximal deviation with respect to the desired trajectory is much smaller for young adults than for elderly one. Furthermore few elderly have the same deviation and it may be considered as a signature of the walking pattern that is worth measuring

Our objective is now to analyze the maneuvers (half-turn and round-about) and to compare/complement the data with the one obtained with a Kinect. A long term objective is also to implement a model of a human walking with a walker and to use this model for an inverse calculation: measuring walking patterns indicators with the walker and calculating these indicators when not using the walker.

6.1.3. *Experimental calibration of a high-accuracy space telescope*

Participants: Thibault Gayral, David Daney, Jean-Pierre Merlet.

A collaborative work began in October 2010 with Thales Alenia Space on the calibration of the mechanical structure of a space telescope. Its architecture is based on a parallel manipulator (type active wrist 6-PUS) used to correct the relative position of two mirrors. The aim is to reach a micrometer accuracy in order to obtain a suitable quality of the images provided by the telescope. Thus, a complete model of the space telescope needs to be developed and validated through calibration. Since high velocity is not required in such an application, the dynamic effects can be neglected and only geometric and/or static calibration has to be considered.

For the geometric models, measurements for calibration were performed in a clean room under controlled pressure, temperature and humidity conditions to minimize the influence of the non-geometric errors. Thus, two possible static inaccuracy sources were identified and modeled: one from the deformation of the mobile platform and the other resulting from the behavior of the flexure joints. Three incremental models of the flexure joints were developed and compared: a spherical joint model, a model issued from the beam theory and a stiffness model. Results of calibration using an accurate measurement system of photogrammetry showed that the flexure joints can be modeled by perfect spherical joints due to the small workspace of the telescope. Concerning the mobile platform deformation, two models were developed. With those models, a positioning accuracy of some micrometers was finally reached after calibration with only position and orientation measurements of the mobile platform.

Then, opto-mechanical models were developed considering experimental measurements by imaging on the prototype of the space telescope. The optical defects were analyzed considering Zernike polynomials. The aim of optical calibration was to minimize the coefficients of the Zernike polynomials in order to improve the optical properties of the space telescope. Results of calibration were studied in order to perform a proper choice of the opto-mechanical models. Finally, the optical quality was improved after calibration. This validates the fact that the telescope can be calibrated directly in space, after its deployment, with only the provided information. A second campaign of measurements by imaging was programmed to finely adjust the opto-mechanical model parameters.

6.2. Miscellaneous results

6.2.1. Symbolic tools for modeling and simulation

Participant: Yves Papegay.

This activity is the main part of a long-term ongoing collaboration with Airbus whose goal is to directly translate the conceptual work of aeronautics engineers into digital simulators to accelerate aircraft design.

An extensive modeling and simulation platform has been designed which includes a dedicated modeling language for the description of aircraft dynamics models in term of formulae and algorithms, and a symbolic compiler producing as target an efficient numerical simulation code ready to be plugged into a flight simulator, as well as a formatted documentation compliant with industrial requirements of corporate memory.

Implementation of this platform is a modeling and simulation environment based on symbolic computation tools. It contains several components :

- a model editor, that makes it possible and easy to enter the whole set of equations describing large and complex industrial models,
- an highly interactive and modular evaluation workbench allowing to simulate the models and to visualize the results inside the modeling environment with the benefits for the designer of being able to directly use all its computational functionalities.
- a C code generator which, using these models, automatically generates the numerical real-time simulation engines
- a technical documentation generator

Technology demonstrated by our prototype has been transferred to our industrial partner in 2012 when final version of our modeling and simulation environment has been delivered to Airbus in November 2012.

However, in 2013, we have worked on several enhancements and extension of functionalities, namely to ease the integration of our environment into the airbus toolbox. Developer level know-how has been transferred to a software company in charge of industrialization and maintenance of the modeling and simulation environment.

6.2.2. Multi-agent aircraft design

Participant: Yves Papegay.

The modeling environment described in the previous section is used, in collaboration with other teams at Airbus, in the framework of the ID4CS project founded by ANR and dedicated to multi-agent optimization of large scale system.

Several models of aircraft engines and of aircrafts have been developed as user cases for the project.

2013 is the last year of the project when agent code based on models has been used to solve several practical optimization problems based on these models.

6.2.3. Equilibrium strategies for linked Electricity and CO2 markets

Participant: Odile Pourtallier.

In collaboration with M. Bossy (Inria -TOSCA Team) and N. Maïzi (CMA - Mines Paristech) O. Pourtallier we have pursued our work on CO2 and electricity market coupling.

The aim of this work is to develop analytic tools, in order to design a relevant mechanism for carbon markets, where relevant refers to emission reduction. In the context of electricity, the number of producers is limited, a standard game theory approach applies. The producers are considered as players behaving on the two financial markets represented here by carbon and electricity. We establish a Nash equilibrium for this non-cooperative J -player game through a coupling mechanism between the two markets.

The original idea comes from the French electricity sector, where the spot electricity market is often used to satisfy peak demand. Producers behavior is demand driven and linked to the maximum level of electricity production. Each producer strives to maximize its market share. In the meantime, it has to manage the environmental burden associated with its electricity production through a mechanism inspired by the EU ETS (European Emission Trading System) framework : each producer emission level must be balanced by a permit or through the payment of a penalty. Emission permit allocations are simulated through a carbon market that allows the producers to buy the allowances at an auction.

Based on a static elastic demand curve (referring to the times stages in an organized electricity market, mainly day-ahead and intra-day), we solve the local problem of establishing a non-cooperative Nash equilibrium for the two coupled markets.