RESEARCH CENTER
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FIELD

Activity Report 2012

Section New Results

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LFANT Project-Team

6. New Results

6.1. Class groups and other invariants of number fields

Participants: Karim Belabas, Jean-François Biasse, Jean-Paul Cerri, Pierre Lezowski.

P. Lezowski extended J.-P. Cerri's algorithm, which was restricted to totally real number fields, to decide whether a generic number field is norm-Euclidean. His procedure allowed to find principal and non norm-Euclidean number fields of various signatures and degrees up to 8, but also to give further insight about the norm-Euclideanity of some cyclotomic fields. Besides, many new examples of generalised Euclidean and 2-stage Euclidean number fields were obtained. The article [31] will appear in *Mathematics of Computation*.

In another direction, norm-Euclidean ideal classes have been studied. They generalise the notion of norm-Euclideanity to non principal number fields. Very few such number fields were known before. A modification of the algorithm provided many new examples and allowed to complete the study of pure cubic fields equipped with a norm-Euclidean ideal class [15].

J.-F.Biasse has determined a class of number fields for which the ideal class group, the regulator, and a system of fundamental units of the maximal order can be computed in subexponential time $L(1/3, O(1))$ (whereas the best previously known algorithms have complexity $L(1/2, O(1))$). This class of number fields is analogous to the class of curves described in [10]. The article [22] has been submitted to *Mathematics of Computation*.

Assuming the GRH, Bach proved that one can calculate the residue of the Dedekind zeta function of a number field K from the knowledge of the splitting of primes $p < X$, with an error bounded explicitly in terms of X and the field discriminant. This is a crucial ingredient in all algorithms used to compute class groups and unit groups in subexponential time (under GRH). Using Weil's explicit formula, K. Belabas improved on Bach's bound, speeding up by a sizable constant factor this part of the class group algorithm. The article has been submitted to *Mathematics of Computation*.

6.2. Number and function fields

Participants: Athanasios Angelakis, Karim Belabas, Pieter Rozenhart.

In joint work with R. Scheidler and M. Jacobson, P. Rozenhart has generalized Belabas's algorithm for tabulating cubic number fields to cubic function fields [17]. This generalization required function field analogues of the Davenport-Heilbronn Theorem and of the reduction theory of binary cubic and quadratic forms. As an additional application, they have modified the tabulation algorithm to compute 3-ranks of quadratic function fields by way of a generalisation of a theorem due to Hasse. The algorithm, whose complexity is quasi-linear in the number of reduced binary cubic forms up to some upper bound X, works very well in practice. A follow-up article [35] describes how to use these results to compute 3-ranks of quadratic function fields, in particular yielding examples of unusually high 3-rank.

In 1976, Onabe discovered that, in contrast to the Neukirch–Uchida results that were proved around the same time, a number field K is not completely characterised by its absolute abelian Galois group A_K. The first examples of non-isomorphic K having isomorphic A_K were obtained on the basis of a classification by Kubota of idele class character groups in terms of their infinite families of Ulm invariants, and did not yield a description of A_K. In [21], A. Angelakis and P. Stevenhagen provide a direct "computation" of the profinite group A_K for imaginary-quadratic K, and use it to obtain many different K that all have the same minimal absolute abelian Galois group.

On March 29–April 2, 2010, a meeting was organized by J.-M. Couveignes, D. Bertrand, Ph. Boalch and P. Debes, at the Luminy CIRM (France) on geometric and differential Galois theories, witnessing the close ties these theories have woven in recent years. The volume [18] collects the proceedings of this meeting. The articles gathered in this volume cover the following topics: moduli spaces of connections, differential equations and coverings in finite characteristic, liftings, monodromy groups in their various guises (tempered fundamental group, motivic groups, generalised difference Galois groups), and arithmetic applications.

Using Galois theory of extension rings, J.-M. Couveignes, R. Lercier and T. Ezome have proposed a new pseudo-primality test in [13]. For every positive integer $k \leq logn$, this test achieves the security of k Miller-Rabin tests at the cost of $k^{1/2} + o(1)$ Miller-Rabin tests. The implementation in Magma shows that this test is competitive for primes with a few thousands digits.

6.3. Quaternion algebras

Participants: Jean-Paul Cerri, Pierre Lezowski, Aurel Page.

With J. Chaubert, J.-P. Cerri and P. Lezowski have studied whether some quaternion fields over number fields are Euclidean, that is to say whether they admit a left or right Euclidean order. In particular, they have established the complete list of totally definite and Euclidean quaternion fields over the rationals or a quadratic number field. Moreover, they have proved that every field in this list is in fact norm Euclidean. The proofs are both theoretical and algorithmic. The article [23] will appear in *International Journal of Number Theory*.

Starting with an order in a suitable quaternion algebra over a number field F with exactly one complex place, one can construct discrete subgroups of $\mathrm{PSL}_2(\mathbb{C})$. These groups, called arithmetic Kleinian groups, act properly discontinuously with finite covolume on the hyperbolic 3-space. In [34], A. Page designs an efficient algorithm which computes a fundamental domain and a presentation for such a group. It is a generalization to the dimension 3 of an algorithm of J. Voight's [44] together with a new, nondeterministic, but faster enumeration procedure. A public implementation is available in KLEINIANGROUPS (see 5.8).

6.4. Complex multiplication and modularity

Participants: Jean-Marc Couveignes, Andreas Enge, Nicolas Mascot, Aurel Page, Damien Robert.

The article by D. Lubicz and D. Robert which explains how to compute an isogeny between two abelian varieties given the kernel (but with different levels of theta structures) has been published [16]. The preprint [25] with R. Cosset and D. Robert extends these method to provide an algorithm constructing the corresponding isogeny without changing the level. This give the first algorithm allowing to compute in polynomial time an isogeny between abelian varieties, and a public implementation is available in AVISOGENIES. The drawback of this algorithm is that it needs the geometric points of the kernel. To compute an isogeny of degree ℓ^g over a finite field, working with geometric points requires to take an extension of degree up to $\ell^g - 1$, and the situation is much worse over a number field. Recently, D. Lubicz and D. Robert have explained how to compute the corresponding isogeny given only the equations of the kernel. This gives a quasi-linear algorithm (in the degree ℓ^g of the isogeny) when ℓ is congruent to 1 modulo 4.

With K. Lauter, D. Robert has worked on improving the computation of class polynomials in genus 2 by the CRT method. The main improvements come from using the above isogeny computation, both to find a maximal curve from a curve in the correct isogeny class, and to find all other maximal curves from one. Further improvements are in the endomorphism ring computation to detect if the curve is maximal, a better sieving of the primes used (and a dynamic selection of them), and the use of the CRT over the real quadratic field rather than over $\mathbb{Q}$ for the case of dihedral CM fields to find factors of the class polynomials. These results have been published at the ANTS conference [30].

With C. Ritzenthaler, Damien Robert has shown how to compute explicitly the Serre obstruction for abelian varieties isogenous to a product of three elliptic curves. This allows to find genus 3 curves with many points over a finite field. The corresponding code has been implemented in an (experimental) version of AVISOGENIES.

In [24], H. Cohen studies several methods for the numerical computation of Petersson scalar products. In particular he proves a generalisation of Haberland's formula to any subgroup of finite index G of $\Gamma = \mathrm{PSl}_2(Z)$, which gives a fast method to compute these scalar products when a Hecke eigenbasis is not necessarily available.

J.-M. Couveignes and B. Edixhoven explore in [19] the relevance of numerical methods in dealing with higher genus curves and their Jacobians. Fast exponentiation is crucial in this context as a stable substitute to Newton's method and analytic continuation. Arakelov theory provides the necessary complexity estimates.

With Reynald Lercier, J.-M. Couveignes has given in [26] a quasi-linear time randomised algorithm that on input a finite field $\mathbb{F}_q$ with q elements and a positive integer d outputs a degree d irreducible polynomial in $\mathbb{F}_q[x]$. The running time is $d^{1+o(1)} \times (\log q)^{5+o(1)}$ elementary operations. The $o(1)$ in $d^{1+o(1)}$ is a function of d that tends to zero when d tends to infinity. And the $o(1)$ in $(\log q)^{5+o(1)}$ is a function of q that tends to zero when q tends to infinity. The fastest previously known algorithm for this purpose was quadratic in the degree. The algorithm relies on the geometry of elliptic curves over finite fields (complex multiplication) and on a recent algorithm by Kedlaya and Umans for fast composition of polynomials.

In [32], N. Mascot shows how to compute modular Galois representations associated with a newform f and the coefficients of f modulo a small prime ℓ. To this end, he designs a practical variant of the complex approximation method presented in the book edited by B. Edixhoven and J.-M. Couveignes [8]. Its efficiency stems from several new ingredients. For instance, he uses fast exponentiation in the modular Jacobian instead of analytic continuations, which greatly reduces the need to compute abelian integrals, since most of the computation handles divisors. Also, he introduces an efficient way to compute arithmetically well-behaved functions on Jacobians. He illustrates the method on the newform Δ, and manages to compute for the first time the associated faithful representation modulo ℓ and the values modulo ℓ of Ramanujan's τ function at huge primes for $\ell \in \{11, 13, 17, 19\}$. In particular, he gets rid of the sign ambiguity stemming from the use of a non-faithful representation as in J. Bosman's work.

A. Enge and R. Schertz determine in [29] under which conditions singular values of multiple η-quotients of square-free level, not necessarily prime to 6, yield class invariants, that is, algebraic numbers in ring class fields of imaginary-quadratic number fields. It turns out that the singular values lie in subfields of the ring class fields of index $2^{k'-1}$ when $k' \geq 2$ primes dividing the level are ramified in the imaginary-quadratic field, which leads to faster computations of elliptic curves with prescribed complex multiplication. The result is generalised to singular values of modular functions on $X_0^+(p)$ for p prime and ramified.

With F. Morain, A. Enge has determined exhaustively under which conditions "generalised Weber functions", that is, simple quotients of η functions of not necessarily prime transformation level and not necessarily of genus 1, yield class invariants [28]. The result is a new infinite family of generators for ring class fields, usable to determine complex multiplication curves. We examine in detail which lower powers of the functions are applicable, thus saving a factor of up to 12 in the size of the class polynomials, and describe the cases in which the polynomials have integral rational instead of integral quadratic coefficients.

6.5. Elliptic curve cryptology

Participants: Jean-Marc Couveignes, Andreas Enge, Damien Robert.

With J.-G. Kammerer, J.-M. Couveignes has given in [14] an appropriate geometric method for studying and classifying encodings into elliptic curves in a cryptographic context. Such encodings were first proposed by Icart in 2009, and later on by Farashahi, Kammerer, Lercier, and Renault. But it was a little bit disappointing to see that it was no more than an application of Tartaglia's result without any geometrical explanations for the existence of such "parameterisations" of elliptic curves. Couveignes and Kammerer have filled this gap by giving exactly what can be expected from geometry: a clear explanation. Moreover, they unify all the recent "parameterisations" of elliptic curves under the same geometric point of view. The approach described in this article uses dual curves with some results coming from intersection theory. The main originality of this work is that these geometrical tools are employed to explain symbolic computations used in cryptography, that is, encoding on elliptic curves.

The survey [20], to be published in the *Handbook of Finite Fields*, presents the state of the art of the use of elliptic curves in cryptography.

6.6. Pairings

Participants: Andreas Enge, Damien Robert, Jérôme Milan.

In [27], A. Enge gives an elementary and self-contained introduction to pairings on elliptic curves over finite fields. For the first time in the literature, the three different definitions of the Weil pairing are stated correctly and proved to be equivalent using Weil reciprocity. Pairings with shorter loops, such as the ate, ate$_i$, R-ate and optimal pairings, together with their twisted variants, are presented with proofs of their bilinearity and non-degeneracy. Finally, different types of pairings are reviewed in a cryptographic context. The article can be seen as an update chapter to [42].

ALEA Project-Team

6. New Results

6.1. Bayesian Nonparametric models for ranked data and bipartite graphs.

In [20], the author develops a novel Bayesian nonparametric model for random bipartite graphs. The model is based on the theory of completely random measures and is able to handle a potentially infinite number of nodes. It is shown that the model has appealing properties and in particular it may exhibit a power-law behavior. Posterior characterization, a generative process for network growth, and a simple Gibbs sampler for posterior simulation are derived. The model is shown to be well fitted to several real-world social networks.

In [21], we develop a Bayesian nonparametric extension of the popular Plackett-Luce choice model that can handle an infinite number of choice items. Our framework is based on the theory of random atomic measures, with the prior specified by a gamma process. We derive a posterior characterization and a simple and effective Gibbs sampler for posterior simulation. We develop a time-varying extension of our model, and apply it to the New York Times lists of weekly bestselling books.

6.2. A new model for polychotomous data

Multinomial logistic regression is one of the most popular models for modelling the effect of explanatory variables on a subject choice between a set of specified options. This model has found numerous applications in machine learning, psychology or economy. Bayesian inference in this model is non trivial and requires, either to resort to a Metropolis-Hastings algorithm, or rejection sampling within a Gibbs sampler. In [19], we propose an alternative model to multinomial logistic regression. The model builds on the Plackett-Luce model, a popular model for multiple comparisons. We show that the introduction of a suitable set of auxiliary variables leads to an Expectation-Maximization algorithm to find Maximum A Posteriori estimates of the parameters. We further provide a full Bayesian treatment by deriving a Gibbs sampler, which only requires to sample from highly standard distributions. We also propose a variational approximate inference scheme. All are very simple to implement. One property of our Plackett-Luce regression model is that it learns a sparse set of feature weights. We compare our method to sparse Bayesian multinomial logistic regression and show that it is competitive, especially in presence of polychotomous data.

6.3. Sparsity-Promoting Bayesian Dynamic Linear Models

Sparsity-promoting priors have become increasingly popular over recent years due to an increased number of regression and classification applications involving a large number of predictors. In time series applications where observations are collected over time, it is often unrealistic to assume that the underlying sparsity pattern is fixed. We propose in [37] an original class of flexible Bayesian linear models for dynamic sparsity modelling. The proposed class of models expands upon the existing Bayesian literature on sparse regression using generalized multivariate hyperbolic distributions. The properties of the models are explored through both analytic results and simulation studies. We demonstrate the model on a financial application where it is shown that it accurately represents the patterns seen in the analysis of stock and derivative data, and is able to detect major events by filtering an artificial portfolio of assets.

6.4. Evolutionnary algorithms and genetic programming

In [22], we consider the identification of a nonlinear system modelled by a nonlinear output error (NOE) model when the system output is disturbed by an additive zero-mean white Gaussian noise. In that case, standard on-line or off-line least squares methods may lead to poor results. Here, our approach is based on evolutionary algorithms. Although their computational cost can be higher than the above methods, these algorithms present some advantages, which often lead to an effortless optimisation. Indeed, they do not need

an elaborate formalisation of the problem. When their parameters are correctly tuned, they avoid to get stuck at a local optimum. To take into account the influence of the additive noise, we investigate different approaches and we suggest a whole protocol including the selection of a fitness function and a stop rule. Without loss of generality, simulations are provided for two nonlinear systems and various signal-to-noise ratios.

The regularity of a signal can be numerically expressed using Hölder exponents, which characterize the singular structures a signal contains. In particular, within the domains of image processing and image understanding, regularity-based analysis can be used to describe local image shape and appearance. However, estimating the Hölder exponent is not a trivial task, and current methods tend to be computationally slow and complex. The paper [17] presents an approach to automatically synthesize estimators of the pointwise Hölder exponent for digital images. This task is formulated as an optimization problem and Genetic Programming (GP) is used to search for operators that can approximate a traditional estimator, the oscillations method. Experimental results show that GP can generate estimators that achieve a low error and a high correlation with the ground truth estimation. Furthermore, most of the GP estimators are faster than traditional approaches, in some cases their runtime is orders of magnitude smaller. This result allowed us to implement a real-time estimation of the Hölder exponent on a live video signal, the first such implementation in current literature. Moreover, the evolved estimators are used to generate local descriptors of salient image regions, a task for which a stable and robust matching is achieved, comparable with state-of-the-art methods. In conclusion, the evolved estimators produced by GP could help expand the application domain of Hölder regularity within the fields of image analysis and signal processing.

One of the main open problems within Genetic Programming (GP) is to meaningfully characterize the difficulty (or hardness) of a problem. The general goal is to develop predictive tools that can allow us to identify how difficult a problem is for a GP system to solve. In [23] and [24], we identify and compare two main approaches that address this question. We denote the first group of methods as Evolvability Indicators (EI), which are measures that attempt to capture how amendable the fitness landscape is to a GP search. The best examples of current EIs are the Fitness Distance Correlation (FDC) and the Negative Slope Coefficient (NSC). The second, more recent, group of methods are what we call Predictors of Expected Performance (PEP), which are predictive models that take as input a set of descriptive attributes of a particular problem and produce as output the expected performance of a GP system. The experimental work presented here compares an EI, the NSC, and a PEP model for a GP system applied to data classification. Results suggest that the EI fails at measuring problem difficulty expressed by the performance of the GP classifiers, an unexpected result. On the other hand, the PEP models show a very high correlation with the actual performance of the GP system. It appears that while an EI can correctly estimate the difficulty of a given search, as shown by previous research on this topic, it does not necessarily capture the difficulty of the underlying problem that GP is intended to solve. Conversely, while the PEP models treat the GP system as a computational black-box, they can still provide accurate performance predictions.

In [32], the goal is to predict the alertness of an individual by analyzing the brain activity through electroencephalographic data (EEG) captured with 58 electrodes. Alertness is characterized here as a binary variable that can be in a "normal" or "relaxed" state. We collected data from 44 subjects before and after a relaxation practice, giving a total of 88 records. After a pre-processing step and data validation, we analyzed each record and discriminate the alertness states using our proposed "slope criterion". Afterwards, several common methods for supervised classification (k nearest neighbors, decision trees (CART), random forests, PLS and discriminant sparse PLS) were applied as predictors for the state of alertness of each subject. The proposed "slope criterion" was further refined using a genetic algorithm to select the most important EEG electrodes in terms of classification accuracy. Results shown that the proposed strategy derives accurate predictive models of alertness.

6.5. Moderate Deviations for Mean Field Particle Models

The article [40] is concerned with moderate deviation principles of a general class of mean eld type interacting particle models. We discuss functional moderate deviations of the occupation measures for both the strong - topology on the space of fi nite and bounded measures as well as for the corresponding stochastic processes on

some class of functions equipped with the uniform topology. Our approach is based on an original semigroup analysis combined with stochastic perturbation techniques and projective limit large deviation methods.

6.6. Bifurcating autoregressive processes

In [42], we investigate the asymptotic behavior of the least squares estimator of the unknown parameters of random coefficient bifurcating autoregressive processes. Under suitable assumptions on inherited and environmental effects, we establish the almost sure convergence of our estimates. In addition, we also prove a quadratic strong law and central limit theorems. Our approach mainly relies on asymptotic results for vector-valued martingales together with the well-known Rademacher-Menchov theorem.

In [46], we study the asymptotic behavior of the weighted least square estimators of the unknown parameters of random coefficient bifurcating autoregressive processes. Under suitable assumptions on the immigration and the inheritance, we establish the almost sure convergence of our estimators, as well as a quadratic strong law and central limit theorems. Our study mostly relies on limit theorems for vector-valued martingales.

In [47], we study the asymptotic behavior of the weighted least squares estimators of the unknown parameters of bifurcating integer-valued autoregressive processes. Under suitable assumptions on the immigration, we establish the almost sure convergence of our estimators, together with the quadratic strong law and central limit theorems. All our investigation relies on asymptotic results for vector-valued martingales.

6.7. Durbin-Watson statistic and first order autoregressive processes

In [45], we investigate moderate deviations for the Durbin-Watson statistic associated with the stable first-order autoregressive process where the driven noise is also given by a first-order autoregressive process. We first establish a moderate deviation principle for both the least squares estimator of the unknown parameter of the autoregressive process as well as for the serial correlation estimator associated with the driven noise. It enables us to provide a moderate deviation principle for the Durbin-Watson statistic in the easy case where the driven noise is normally distributed and in the more general case where the driven noise satisfies a less restrictive Chen-Ledoux type condition.

In [51], we investigate the asymptotic behavior of the Durbin-Watson statistic for the general stable $p-$order autoregressive process when the driven noise is given by a first-order autoregressive process. We establish the almost sure convergence and the asymptotic normality for both the least squares estimator of the unknown vector parameter of the autoregressive process as well as for the serial correlation estimator associated with the driven noise. In addition, the almost sure rates of convergence of our estimates are also provided. Then, we prove the almost sure convergence and the asymptotic normality for the Durbin-Watson statistic. Finally, we propose a new bilateral statistical procedure for testing the presence of a significative first-order residual autocorrelation and we also explain how our procedure performs better than the commonly used Box-Pierce and Ljung-Box statistical tests for white noise applied to the stable autoregressive process, even on small-sized samples.

6.8. Markovian superquadratic BSDEs

In [Stochastc Process. Appl., 122(9):3173-3208], the author proved the existence and the uniqueness of solutions to Markovian superquadratic BSDEs with an unbounded terminal condition when the generator and the terminal condition are locally Lipschitz. In [50], we prove that the existence result remains true for these BSDEs when the regularity assumptions on the generator and/or the terminal condition are weakened.

6.9. Non-Asymptotic Analysis of Adaptive and Annealed Feynman-Kac Particle Models

Sequential and Quantum Monte Carlo methods, as well as genetic type search algorithms can be interpreted as a mean field and interacting particle approximations of Feynman-Kac models in distribution spaces. The performance of these population Monte Carlo algorithms is strongly related to the stability properties

of nonlinear Feynman-Kac semigroups. In [49], we analyze these models in terms of Dobrushin ergodic coefficients of the reference Markov transitions and the oscillations of the potential functions. Sufficient conditions for uniform concentration inequalities w.r.t. time are expressed explicitly in terms of these two quantities. We provide an original perturbation analysis that applies to annealed and adaptive FK models, yielding what seems to be the first results of this kind for these type of models. Special attention is devoted to the particular case of Boltzmann-Gibbs measures' sampling. In this context, we design an explicit way of tuning the number of Markov Chain Monte Carlo iterations with temperature schedule. We also propose and analyze an alternative interacting particle method based on an adaptive strategy to define the temperature increments.

6.10. A Robbins-Monro procedure for a class of models of deformation

The paper [48] deals with the statistical analysis of several data sets as- sociated with shape invariant models with different translation, height and scaling parameters. We propose to estimate these parameters together with the common shape function. Our approach extends the recent work of Bercu and Fraysse to multivariate shape invariant models. We propose a very efficient Robbins-Monro procedure for the estimation of the translation parameters and we use these esti- mates in order to evaluate scale parameters. The main pattern is estimated by a weighted Nadaraya-Watson estimator. We provide almost sure convergence and asymptotic normality for all estimators. Finally, we illustrate the convergence of our estimation procedure on simulated data as well as on real ECG data.

6.11. Individual load curves intraday forecasting

A dynamic coupled modelling is investigated to take temperature into account in the individual energy consumption forecasting. The objective in [44] is both to avoid the inherent complexity of exhaustive SARIMAX models and to take advantage of the usual linear relation between energy consumption and temperature for thermosensitive customers. We first recall some issues related to individual load curves forecasting. Then, we propose and study the properties of a dynamic coupled modelling taking temperature into account as an exogenous contribution and its application to the intraday prediction of energy consumption. Finally, these theoretical results are illustrated on a real individual load curve. The authors discuss the relevance of such an approach and anticipate that it could form a substantial alternative to the commonly used methods for energy consumption forecasting of individual customers.

BACCHUS Team

6. New Results

6.1. Residual distribution schemes

Participants: Rémi Abgrall [Corresponding member], Mario Ricchiuto, Dante De Santis, Algiane Froehly, Cécile Dobrzynski.

We have understood how to approximate the advection diffusion problem in the context of residual distribution schemes. A third order version for scalar problem has been written. It is uniformly accurate, from pure viscous to pure convection problems. This scheme has been generalised to the laminar Navier Stokes equations. An extension to the turbulent case (with Spalart Allmaras model) has also been written and tested. We have studied the (iterative) convergence issues using Jacobian Free techniques or the LUSGS algorithm. Tests in two and three dimensions have been carried out. This work is submitted in [37] and has been the topic of [20].

A. Froehly has submitted her PhD thesis about the extension of the residual distribution scheme using isogeometric analysis. In particular, we have foccussed on mesh adaption, including at the boundary. A paper is being written to summarized the work.

6.2. Curved meshes

Participants: Rémi Abgrall, Cécile Dobrzynski [Corresponding member], Algiane Froehly.

One of the main open problems in high order schemes is the design of meshes that fit with enough accuracy the boundary of the computational domain. If this curve/surface is not locally straight/planar, the elements must be curved near the boundary, and their curvature need to be propagated to the interior of the domain to have valid elements. When the mesh is very streched, this can be quite challenging since, in addition, we want that the mesh keep a structure, in particular for boundary layers. Using tools explored in isogeometrical analysis, we have been able to construct a prototype computing curved meshes (in 2D and 3D), while keeping the structure of the mesh.

6.3. Hypoelastic models

Participants: Rémi Abgrall [Corresponding member], Pierre-Henri Maire.

In collaboration with CEA (P.H. maire), we have developped and tested a new finite volume like algorithm able to simulate hypoelastic-plastics problems on unstructured meshes. This has been published in [47].

6.4. Penalisation methods using unstructured meshes

Participants: Rémi Abgrall, Cécile Dobrzynski, Héloïse Beaugendre [Corresponding member].

In Computational Fluid Dynamics the interest on embedded boundary methods for Navier-Stokes equations increases because they simplify the meshing issue, the simulation of multi-physics flows and the coupling of fluid-solid interactions in situation of large motions or deformations. Nevertheless, an accurate treatment of the wall boundary conditions remains an issue of these methods. In this work we develop an immersed boundary method for unstructured meshes based on a penalization technique and we use mesh adaption to improve the accuracy of the method close to the boundary. The idea is to combine the strength of mesh adaptation, that is to provide an accurate flow description especially when dealing with wall boundary conditions, to the simplicity of embedded grids techniques, that is to simplify the meshing issue and the wall boundary treatment when combined with a penalization term to enforce boundary conditions. The bodies are described using a level-set method and are embedded in an unstructured grid. Once a first numerical solution is computed mesh adaptation based on two criteria the level-set and the quality of the solution is performed.

6.5. Unsteady problem

Participants: Rémi Abgrall, Mario Ricchiuto [Corresponding member], Luca Arpaia, Jan Klosa.

Using a reinterpretation of the explicit RD scheme we had designed 2 years ago, we have been able to construct a third order accurate RD scheme in one space dimension. The extension to multidimensional problems is pending.

We have studied the extention of second order unsteady RD scheme to the ALE formulation. New version of the explsiict unsteady RD schemes have been studied.

6.6. Lagrangian hydrodynamics

Participants: Rémi Abgrall [Corresponding member], Pierre-Henri Maire, François Vilar.

F. Vilar has achieved his thesis on the approximation of the Euler equations written in pure Lagrangian coordinates. He has foccussed on third order accuracy in time and space, usning a Discontinuous Galerkin formulation. The solution is approximated localy by quadratic polynomials. The boundary of elements are approximated by Bezier curves. He has managed to achieve an approximation consistant with the geometric Cosnervation Law. Many test cases have been computed, showing both a dramatic improvement of the accuracy and the robustness of the method with respect to its second order counterpart.

6.7. Boundary Layer Enrichment

Participants: Rémi Abgrall [Corresponding member], Arnaud Krust.

Arnaud Krust has finished his PhD thesis on boundary layer enrichment. We developed a numerical framework well suited for advection- diffusion problems when the advection part is dominant. In that case, given Dirichlet type boundary condition, it is well known that a boundary layer develops. In order to resolve correctly this layer, standard methods consist in increasing the mesh resolution and possibly increasing the formal accuracy of the numerical method. In this work, we follow another path: we do not seek to increase the formal accuracy of the scheme but, by a careful choice of finite element, to lower the mesh resolution in the layer. Indeed the finite element representation we choose is locally the sum of a standard one plus an enrichment. This work proposes such a method and with several numerical examples, we show the potential of this approach. In particular we show that the method is not very sensitive to the choice of the enrichment functions. The best choice of enrichment are shown to be obtained by an iterative mechanisms which bears some common features with mesh refinement.

6.8. Uncertainty Quantification

Participants: Rémi Abgrall, Pietro Congedo [Corresponding member], Gianluca Geraci, Mario Ricchiuto.

We developed two research lines: the first one focused on the computation of high-order statistics, the second one is related to the formulation of a global framework in the coupled physical/stochastic space. First, we proposed a formulation in order to compute the decomposition of high-order statistics. The idea is to compute the most influential parameters for high orders permitting to improve the sensitivity analysis. Second objective is to illustrate the correlation between the high-order functional decomposition and the PC-based techniques, thus displaying how to compute each term from a numerical point of view. Secondly, Basing on the Harten multiresolution framework in the stochastic space, we proposed a method allowing an adaptive refinement/derefinement in both physical and stochastic space for time dependent problems. As a consequence, an higher accuracy is obtained with a lower computational cost with respect to classical non-intrusive approaches, where the adaptivity is performed in the stochastic space only. Performances of this algorithm are tested on scalar Burgers equation and Euler system of equations, comparing with the classical Monte Carlo and Polynomial Chaos techniques.

Application of some of these techniques to tsunami simulations have been conducted.

6.9. Robust Design Optimization

Participant: Pietro Congedo [Corresponding member].

The Simplex-Simplex approach, that has been proposed in 2011, has been further developed. In particular, the algorithm has been improved yielding an evolved version of the Simplex2 approach, and the formulation has been extended to treat mixed aleatory/epistemic uncertainty. The resulting SSC/NM (Simplex Stochastic Collocation/Nelder-Mead) method, called Simplex2, is based on i) a coupled stopping criterion and ii) the use of an high-degree polynomial interpolation of the optimization space. Numerical results show that this method is very efficient for mono-objective optimization and minimizes the global number of deterministic evaluations to determine a robust design. This method is applied to some analytical test cases and a realistic problem of robust optimization of a multi-component airfoil. In this work, we present an extension of this method for treating epistemic uncertainty in the context of interval analysis approach. This method consists in a multi-scale strategy based on simplex space representation in order to minimize global cost of mixed epistemic-aleatory uncertainty quantification. This reduction is obtained i) by a coupled stopping criterion, ii) by an adaptive polynomial interpolation that could be used as a response surface in order to accelerate optimization convergence, iii) by a simultaneous min/max optimization sharing the same interpolating polynomials at each iteration [.....].

6.10. Multiphase flows

Participants: Rémi Abgrall [Corresponding member], Pietro Congedo, Maria-Giovanna Rodio, Harish Kumar.

We developed the numerical solver based on a DEM formulation modified for including viscous effects and a more complex equation of state for the vapor region. The method used is the DEM for the resolution of a reduced five equation model with the hypothesis of pressure and velocity equilibrium , without mass and heat transfer. This method results in a well-posed hyperbolic systems, allowing an explicit treatment of non conservative terms, without conservation error. The DEM method directly obtains a well-posed discrete equation system from the single-phase conservation laws, producing a numerical scheme which accurately computes fluxes for arbitrary number of phases. We considered two thermodynamic models , i.e. the SG EOS and the Peng-Robinson (PR) EOS. While SG allows preserving the hyperbolicity of the system also in spinodal zone, real-gas effects are taken into account by using the more complex PR equation. The higher robustness of the PR equation when coupled with CFD solvers with respect to more complex and potentially more accurate multi-parameter equations of state has been recently discussed. In this paper, no mass transfer effect is taken into account, thus the PR equation can be used only to describe the vapor behavior, while only the SG model is used for describing the liquid.

Another topic covered by Bacchus is about the numerical approximation of non conservative systems. One very interetsing example is obtained by the Kapila model, for which shock relations can be found from physical principles. Most, if not all, the know discretisation are at best stable, but do not converge under mesh refinement. We have proposed a way to do so by using some modifications of a Roe-like solver.

6.11. Parallel remeshing

Participants: Cécile Dobrzynski, Cédric Lachat, François Pellegrini [Corresponding member].

Our studies regarding parallel remeshing use a dedicated software framework called `PaMPA` (for "*Parallel Mesh Partitioning and Adaptation*"; see Section 5.6 for more details about it). This software, whose development started three years ago, allow one to describe distributed meshes in an abstract way.

The work carried out this year concerns the definition of suitable algorithms for performing remeshing in parallel, using a sequential remesher. To do so, areas suitable for remeshing (that is, cells for which a quality measurement routine indicates that remeshing is necessary) are grouped into boules of a size small enough to be handled by a sequential remesher, and big enough so that this remesher can do useful work on each of the boules. The core of the work is therefore to identify and build relevant boules, to send them to as many processors as possible, to remesh them sequentially, and to merge the remeshed boules into what remains of the original mesh. Then, areas that have not already been processed (e.g. areas at the interface of two or more boules) can be considered in turn, until all relevant cells have been considered. The structure and operations of `PaMPA` have been presented in [29].

Several algorithms have been experimented in order to build the boules. The one which proved the most efficient is based on a partitioning of an induced subgraph of the element graph, using the `PT-Scotch` tool which is already used for mesh redistribution. `PaMPA` has been interfaced with `MMG3D` in order to create a demonstrator for remeshing in parallel tetraedral meshes. A set of tetrahedral cube-shaped test meshes has been created, with a metric that coerces remeshing in the interior of the cubes. `PaMPA` was able to remesh a 12 million tetrahedral mesh into 18 million tetrahedra on 80 processors, yielding a quality equivalent to the one of the sequential remesher used alone. Scalability experiments on much larger test cases are in progress; yet, their quality will no longer be comparable to a sequential test case. This version of `PaMPA` will soon be released and made available to the community.

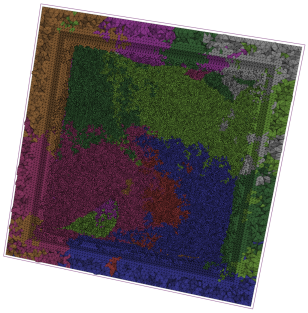


Figure 4. Cut of a 3D cube made of tetrahedra showing the effect of parallel remeshing by `PaMPA`.

6.12. Parallel graph remapping

Participants: Sébastien Fourestier, François Pellegrini [Corresponding member].

Last year, a set of new algorithms for sequential remapping and mapping with fixed vertices has been devised. These algorithms had been intergrated in the `Charm++` parallel environment, in the context of a collaboration with the Joint Laboratory for Petascale Computing (JLPC) between Inria and UIUC.

These algorithms have been integrated in version `6.0` of `Scotch`, which has been released in the beginning of December. This release also comprises new threaded formulations of the critical and most time-consuming algorithms used in graph partitioning, namely: graph coarsening and our diffusion-based method.

All the remapping algorithms that have been designed last year were meant to be easily parallelizable. The work of this year has been to derive and implement their parallel formulation. This is now the case, which completes this five year long work. These algorithms, which offer a quality similar to the one of the sequential algorithms, will be released in version `6.1` of `Scotch`.

6.13. Sparse matrix reordering for ILU solvers

Participants: Astrid Casadei, Sébastien Fourestier, François Pellegrini [Corresponding member].

In the context of ANR PETALh, our task is to find ways of reordering sparse matrices so as to improve the robustness of incomplete LU factorization techniques. The path we are following is to favor the diagonal dominance of the matrices corresponding to the subdomains of the Schur complement. Our studies aim at injecting some information regarding off-diagonal numerical values into nested dissection like reordering methods, so as to favor the preservation of high off-diagonal values into either the subdomains or the separators of Schur complement techniques.

This year, we have set-up a software testbed for experimenting such methods. It comprises a modified version of the Scotch sparse matrix ordering library for computing orderings and of the HIPS iterative sparse linear system solver for evaluating them. The text cases used are provided by the industrial partners of the PETALh project.

Our first experiments show that injecting information regarding off-diagonal terms can indeed improve convergence. However, many parameters have to be evaluated in a thorough experimentation plan. Since Scotch uses integer terms only, some scaling has to be performed, which imposes to determine how to scale the coefficients (type of scaling and range), whether to filter small values, etc. This work is in progress.

6.14. Subdomain decomposition

Participants: Astrid Casadei, François Pellegrini, Pierre Ramet [Corresponding member].

This work aims at finding subdomain decompositions that balance the sizes of off-diagonal contribution blocks.

In terms of graph partitioning, we have expressed this problem as a multi-constraint partitioning problem. In addition to bearing a weight that expresses the workload associated with its degrees of freedom, every graph vertex bears a second weight that holds the number of unknowns to which it is linked outside of its subdomain. Hence, in the nested dissection process, every time a separator is computed, this second weight is updated for each frontier vertex of the separated parts, before they are also recursively separated.

This year, we have set-up a software testbed for experimenting this approach. The Scotch sparse matrix ordering library has been modified so that graph vertices can bear multiple vertex weights. This required a slight change in the interfaces, but also modifications of the internal handling of graphs in many modules (nested dissection, graph coarsening, etc).

6.15. Development of a simulation code for rarefied gas flows

Participants: Luc Mieussens [Corresponding member], Florent Pruvost [IMB, engineer].

The simulation code CORBIS (rarefied gases in 2 space dimensions on structured meshes) has been entirely modified: modular form, use of the git version control system, modification to use unstructured meshes, MPI/OpenMP hybrid parallelization. Very good performance in terms of scalability and efficiency have been obtained, up to 700 cores.

6.16. Numerical methods for high altitude aerodynamics

Participants: Luc Mieussens [Corresponding member], N. Hérouard [CEA-CESTA, PhD].

In collaboration with CEA-CESTA, we have worked on the following subjects.

- A new method to generate locally refined velocity grids has been proposed. Very high performance improvement have been obtained (acceleration of the CPU time by a ratio around 30 for 3D computations). This work has been published in the proceedings of the 28th Symposium on rarefied Gas Dynamics, and is the subject of a paper submitted for publication.
- The second order Discontinuous Galerkin method has been studied for a one-dimensional problem of rarefied gases: we have shown that this method is clearly more accurate and faster than our finite volume method (which was used up to fourth order). This study will be developed in 2013 (numerical analysis and application to 2D problems).

6.17. Numerical methods for rarefied gas flows around moving obstacles

Participants: Luc Mieussens [Corresponding member], G. Dechristé [IMB, PhD].

We have presented one of the first numerical simulation of the Crookes radiometer. This phenomenon, due to the thermal creep flow, has been simulated with a Cartesian grid approach, with a cut-cell techniques that allow for an accurate treatment of solid boundaries. This work has been published in the proceedings of the 28th Symposium on rarefied Gas Dynamics.

6.18. Fast numerical methods for rarefied gases

Participants: Luc Mieussens [Corresponding member], Stéphane Brull [IMB], L. Forestier-Coste [IMB, Post Doc].

We have proposed a new method to discretize kinetic equations. It is basedd on a discretization of the velocity variable which is local in time and space. This induces an important gain in term of memory storage and CPU time, at least for 1D problems (this work has been rpesented in a paper submitted for publication). Two-dimensional extensions are under development.

6.19. Asymptotic Preserving schemes for the linear transport

Participant: Luc Mieussens [Corresponding member].

We have shown that the recent method "Unified Gas Kinetic Scheme", proposed by K. Xu to simulated multiscale rarefied gas flows, can be extended to other fields, like radiative transfer. This approach, based on a simple finite volume technique, is very general and can be easily applied to complex geometries with unstructured meshes. This work has been presented in a paper submitted for publication.

CAGIRE Team

6. New Results

6.1. Low Mach number flows simulations issue

The time-step dependency and the scaling of the pressure-velocity coupling suitable for unsteady calculations of low Mach number flows including acoustic features has been identified in the Momentum Interpolation approach. It has been shown that the proper form of the inertia term in the transporting velocity definition is related to the time-step independency of the steady state. The suitable scaling of the pressure gradient dissipation has been used to suggest a modification of AUSM+-up that allows acoustic simulations of low Mach number flows. The accuracy improvement when the solution is compared to the one of the original AUSM+-up scheme indicates that the scaling identified in the Momentum Interpolation approach can be applied with advantage to Godunov-type schemes [3].

6.2. Experimental results

The MAVERIC test facility has been significantly upgraded with the acquisition of a complete GPU-based system (hardware+software) that speeds up by a factor of 10 the processing of the PIV data. The strong sensitivity of the flow topology to the presence of an acoustic standing wave in the cross-flow has been clearly evidenced. The presently available measurements give already the possibility of extracting numerous velocity profiles for a future fruitful LES assessment. The dedicated 1-jet experiment for DNS assessment will start at the beginning of 2013 [8].

CONCHA Project-Team

6. New Results

6.1. Convergence of adaptive finite element algorithms

Participants: Roland Becker, Shipeng Mao, David Trujillo.

The theoretical analysis of mesh-adaptive methods is a very active field of research. We have generalized our previous results concerning optimality of adaptive methods to nonconforming finite elements [53]. Our results include the error due to iterative solution of the system matrices by means of a simple stopping criterion related to the error estimator. The main difficulty was the treatment of the nonconformity which leads to a perturbation of the orthogonality relation at the heart of the proofs for conforming finite elements. We have been able to extend this result to the Stokes equations, considering different lowest-order nonconforming finite elements on triangular and quadrilateral meshes [16].

In [19] we have shown that the smallness assumption required in all former proofs of optimality of adaptive finite element methods can be overcome, at least in some situations.

Finally, we have shown optimality of a new goal-oriented method in [21].

Our theoretical studies, which are motivated by the aim to develop better adaptive algorithms, have been accompanied by software implementation with the Concha library, see Section 5.1 . It hopefully opens the door to further theoretical and experimental studies.

6.2. Finite element methods for interface problems

Participants: Nelly Barrau, Roland Becker, Robert Luce.

The original formulation of NXFEM [63] is based on the doubling of elements. In some situations, as the case of a moving interface, it is computationally more convenient to have a method with local enrichment, as for the standard XFEM. In [47] we have developed such an approach based on NXFEM. We have developed an hierarchical formulation for a fictitious domain formulation in [7].

One of the technical difficulties is the simultaneous robustness of the method with respect to the size of the intersection of a mesh cell with the interface and with respect to the discontinuous diffusion parameters. In [ ] (note CRAS 2012) we proposed a modified formulation of the NXFEM which allows us to obtain this robustness to solve the Darcy equation.

In connection with the thesis of Nelly Barrau, supervised by Robert Luce and Eric Dubach (LMAP) we have:

- implemented lots of geometrical tools in 2D and 3D necessary to use the NXFEM methods,
- extended the method to P_k and Q_k finite elements ([42],
- generalized the residual estimator and developed an adaptative process with hanging node (8),
- adapted the method to the transport equation.

6.3. A posteriori error estimators based on $H(\mathrm{div})$-reconstructed fluxes

Participants: Roland Becker, Daniela Capatina, Robert Luce.

Mesh adaptivity is nowadays an essential tool in numerical simulations; in order to achieve it, reliable and efficient, easily computable *a posteriori* error estimators are needed. Such estimators obtained by reconstructing locally conservative fluxes in the Raviart-Thomas finite element space have been largely employed in the past years.

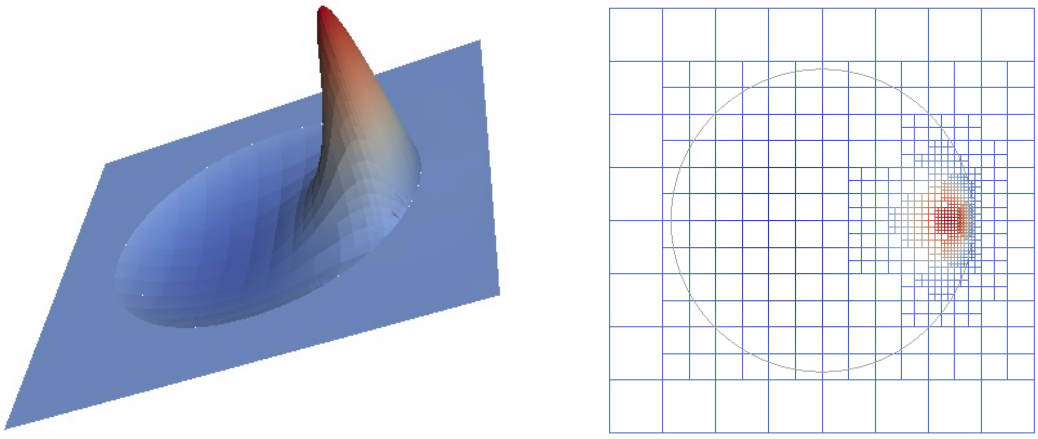


Figure 8. Result of an adaptative process with hanging node

We have so far considered the convection-diffusion equation and proposed a unified framework for several finite element approximations (conforming, nonconforming and discontinuous Galerkin). The main advantage of our approach is to use, contrarily to the existing references, only the primal mesh for the flux reconstruction, which presents certain facilities from a computational point of view.

For this purpose, the construction of the $H(\mathrm{div})$-vector involved in the error estimator is inspired by the hypercircle method cf. [56] and is achieved on patches, which may overlap. A patch depends on the type of the employed finite elements and is defined as the support of a basis function.

Our first results were presented in [12]. We are working on the extension to higher-order approximations, to quadrilateral meshes and to other model problems.

6.4. Discretization of Euler's equations

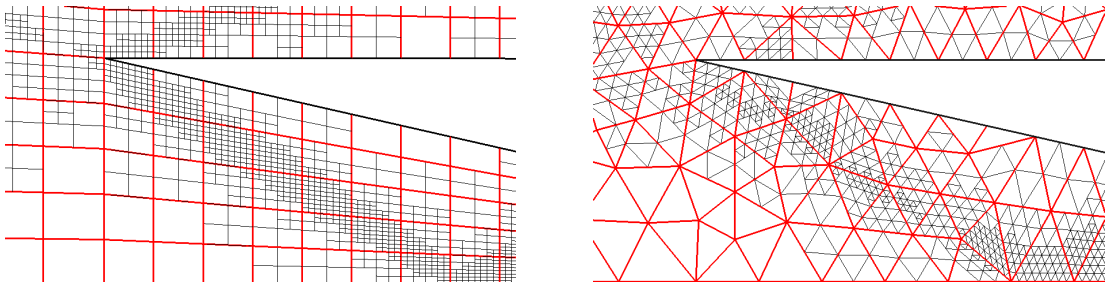
Participants: Roland Becker, Kossivi Gopki, Eric Schall, David Trujillo.

Over the past years, significant advances have been made in developing discontinuous Galerkin finite element methods (DGFEM) for applications in fluid flow and heat transfer. Certain features of the method have made it attractive as an alternative to other popular methods such as finite volume and more convenient finite element methods in thermal fluid engineering analyses. The DGFEM has been used successfully to solve hyperbolic systems of conservation laws. It makes use of the same local function space as the continuous method, but with relaxed continuity at inter-element boundaries. Since it uses discontinuous piecewise polynomial bases, the discretization is locally conservative and in the considered lowest-order case, the method preserves the maximum principle for scalar equations.

One of the challenges in Computational Fluid Dynamic (CFD) is to obtain as accurate as possible the solution of the problem under consideration at very low cost in terms of computational time. So our principal work is to find some relevant and robust strategies and technics of meshes adaptation in order to concentrate just the calculation where there are physical phenomena to capture. From Industrial point of view, the aim is to get the stationary solution as quick as possible with as much accuracy as possible. The main limitation of these results in CFD concern the underlying models: for example, nearly nothing seems to be known for (even linear) first-order systems or for realistic nonlinear equations. We therefore have developed different modern techniques, especially adaptive methods, to tackle this kind of problems in compressible CFD. The strategy is to iteratively improve the quality of the approximate solutions based on computed information (a posteriori error analysis).

In this way, a sequence of locally refined meshes is constructed, which allows for better efficiency as compared to more classical approaches in the presence of different kind of singularities. The main goal is to improve the aerodynamical design process for complex configurations by significantly reducing the time from geometry to solution at engineering-required accuracy using high-order adaptive methods.

One of our strategies of refinement is based on the creation of hanging nodes commonly called non-conforming refinement. The figures 9 show superposition of two kinds of meshes. One is a non-conforming refined mesh (black color) and the other one is the initial grid (red color) on which the refinement has been performed. It shows the technic of cutting the cells where singularities occur in the scramjet inlet.



(a) (b)

Figure 9. Superposition of non-conforming adapted black color) grid and initial grid (red color) – (a) quadrangles and (b) triangles.

The mesh adaptation is designed using some criteria as a posteriori error estimates. We have designed criteria based on the calculation of the jump of physical quantities like density, pressure, entropy, temperature and mach number at the inter-element. This criteria seems to be a very good indicator for the mesh adaptation. Figure 10 is the comparison of isoline of the density in scramjet internal flow at mach 3 of the initial mesh, the third and the sixth mesh after refinement.The indicator used is the density jump. It shows the impact and the accuracy of the solution obtained after the sixth iteration of the refinement.

The figure 11 shows the streamlines of the density in the scramjet inlet after the seventh iteration. This shows how the adaptation depicts almost clearly and accurately the shock waves and the expansion waves and their interactions in the domain.

Figure 12 represent the density isolines of a flow past cylinder test case using the non-conforming mesh adaptation with quadrangular an triangular girds.

We have also settled another indication which is hierarchical. It measures the difference of g_h with the physical quantity $g_{h/2}$ obtained by computation on a globally refined mesh $h/2$. This allows us the make comparison with the previous indicator. The case test considered for this comparison is an external flows past a cylinder airfoil at fixed free stream conditions : $M_\infty = 3$. The result is quite surprising the way one type of indicator can capture phenomenon that are not capture by the another one. In fact the hierarchical indicator seems to capture recirculation downstream to the obstacle which was not capture by the jump indicator (see figure 13)

We compare the computational time between a non-conforming mesh refinement and a globally mesh refined with nearly the same amount of cells. The meshes contain quadrangles or triangles. We can observe trough the following tables that the adapted meshes wether triangular or quadrangular meshes allow to save 20 to 90 times the computational time than the normal globally refined mesh. (see tables 1 and 2)

In table 1, the gain in time is 35 times in quadrangular grid case and 90 times triangular ones and in table 2, the gain in time: 18 times in quadrangular grid case and 58 times triangular ones. So one can say that the

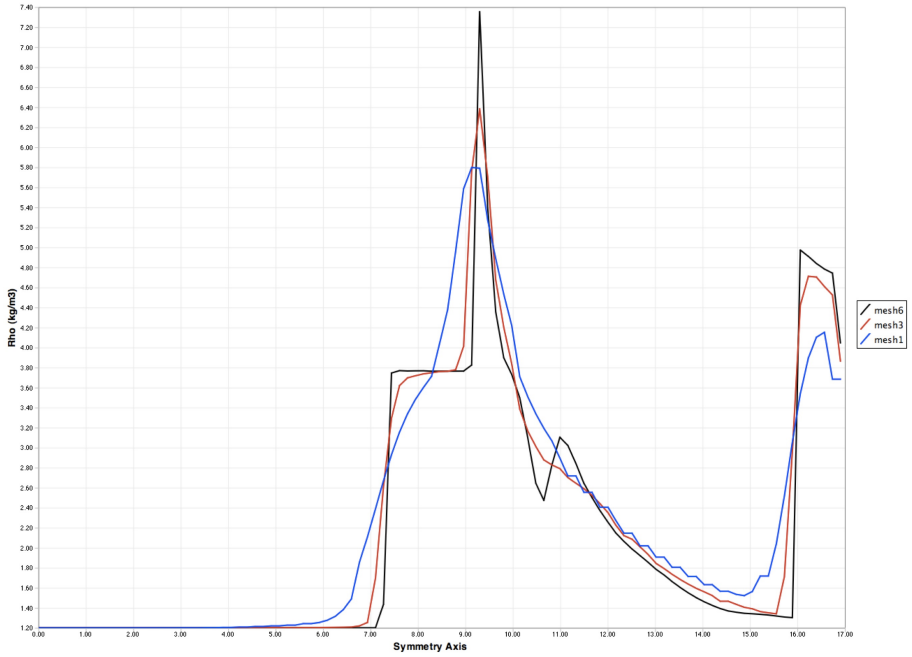


Figure 10. Cutlines along the symmetry axis of various meshes for the scramjet test case

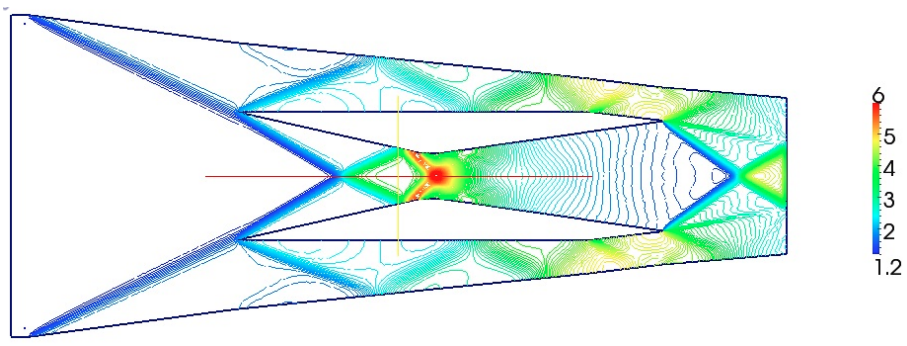
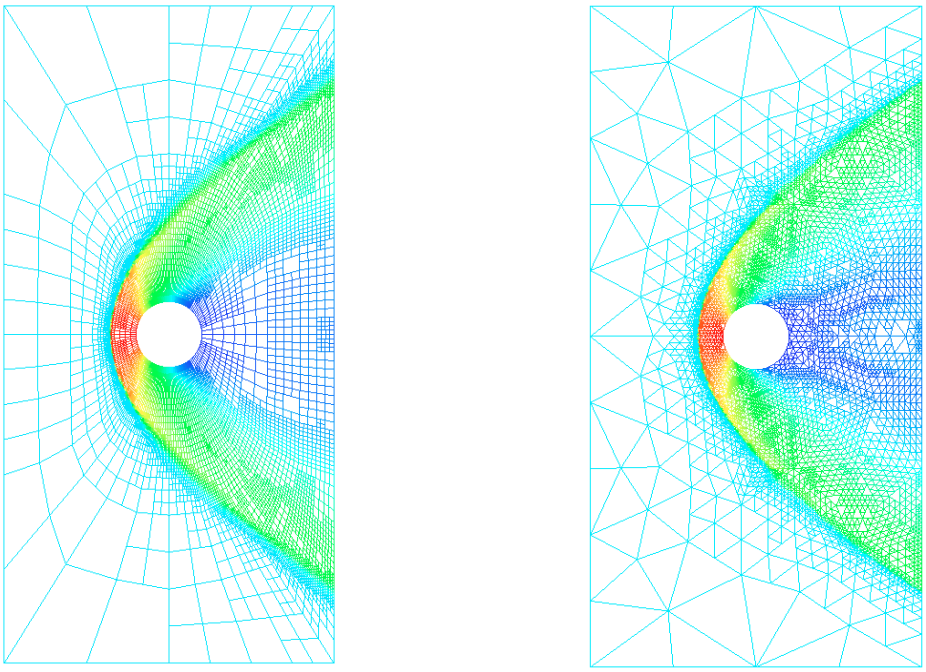
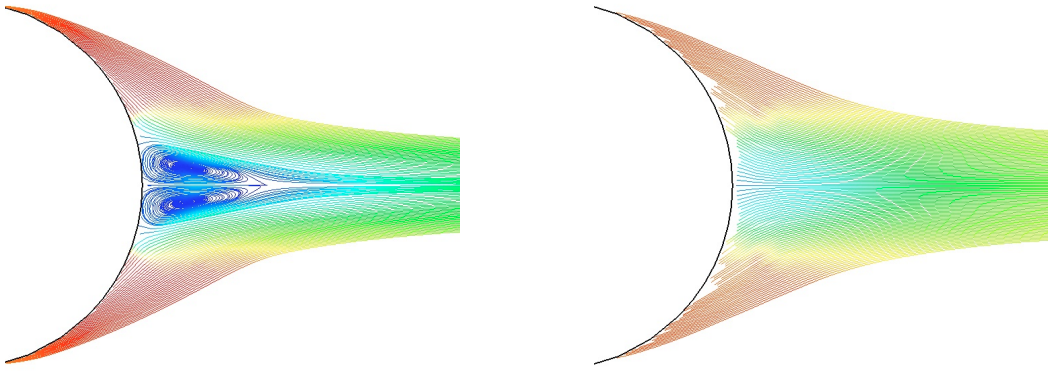


Figure 11. Density streamlines on grid obtained after the seveneth iteration of adaptive refinement procedure with density jump as indicator



(a) (b)

Figure 12. Locally adapted mesh on quadrilaterals (a) and triangles (b)



(a) (b)

Figure 13. Streamlines coloured by the density on meshes generated with hierarchical indicator (a) and with jump indicator (b)

Scramjet test case at mach=3

	Nodes	Cells	Segments	Compt. Time(s)
Scram_Quad_4	17043	15485	34308	25.0236
Scram_Quad_Uniform	17183	16640	33824	865.0177
Scram_Tri_4	9951	17005	29138	22.3141
Scram_Tri_Uniform	13295	25504	38800	2000.4269

Table 1

Flow past cylinder test case at mach=3

	Nodes	Cells	Segments	Compt. Time(s)
Cyl_Quad_5	11203	10174	23105	47.2187
Cyl_Quad_Uniform	10496	10240	20736	814.6168
Cyl_Tri_6	6480	10867	19264	79.7836
Cyl_Tri_Uniform	6032	11776	17808	4258.6618

Table 2

Figure 14. Comparison of computational times

adaptive mesh with the strategies and technics we have settled are efficient and robust in capturing physical phenomenon at a very reasonable low cost.

In concluding, the procedure of refinement permit to save computational time and have good accuracy of the approximated solution computed. Our focus is to continue the improve our methods and strategies in order to meet the requirement of accuracy, robustness and efficiency. Many other works are in hand such as slope limiters for high-order Discontinous Galerkin, low mach number computation with some remarkable approaches.

CQFD Project-Team

5. New Results

5.1. Singularly Perturbed Discounted Markov Control Processes in a General State Space

Participant: François Dufour.

Markov decision processes, optimal control, infinite discounted expected cost, optimal control, singular perturbation

In this work, it is studied the asymptotic optimality of discrete-time Markov Decision Processes (MDP's in short) with general state space and action space and having weak and strong interactions. The idea in this work is to consider a MDP with general state and action spaces and to reduce the dimension of the state space by considering an averaged model. This formulation is often described by introducing a small parameter $\epsilon > 0$ in the definition of the transition kernel, leading to a singularly perturbed Markov model with two time scales. Our objective is twofold. First it is shown that the value function of the control problem for the perturbed system converges to the value function of a limit averaged control problem as ϵ goes to zero. In the second part of this work, it is proved that a feedback control policy for the original control problem defined by using an optimal feedback policy for the limit problem is asymptotically optimal. Our work extends existing results of the literature in the following two directions: the underlying MDP is defined on general state and action spaces and we do not impose strong conditions on the recurrence structure of the MDP such as Doeblin's condition.

These results have been obtained in collaboration with Oswaldo Luis Do Valle Costa from Escola Politécnica da Universidade de São Paulo, Brazil.

It has been published in SIAM Journal of Control and Optimization [16].

5.2. The expected total cost criterion for Markov decision processes under constraints: a convex analytic approach.

Participant: François Dufour.

Markov decision process, expected total cost criterion, constraints, linear programming, occupation measure

This work deals with discrete-time Markov Decision Processes (MDP's) under constraints where all the objectives have the same form of an expected total cost over the infinite time horizon. The existence of an optimal control policy is discussed by using the convex analytic approach. We work under the assumptions that the state and action spaces are general Borel spaces and the model is non-negative, semi-continuous and there exists an admissible solution with finite cost for the associated linear program. It is worth noting that, in contrast with the classical results of the literature, our hypotheses do not require the MDP to be transient or absorbing. Our first result ensures the existence of an optimal solution to the linear program given by an occupation measure of the process generated by a randomized stationary policy. Moreover, it is shown that this randomized stationary policy provides an optimal solution to this Markov control problem. As a consequence, these results imply that the set of randomized stationary policies is a sufficient set for this optimal control problem. Finally, our last main result states that all optimal solutions of the linear program coincide on a special set with an optimal occupation measure generated by a randomized stationary policy. Several examples are presented to illustrate some theoretical issues and the possible applications of the results developed in the paper.

These results have been obtained in collaboration with Alexey Piunovskiy from Department. of Mathematical Sciences, The University of Liverpool, United Kingdom and with Masayuki Horiguchi form the Department of Mathematics, Faculty of Engineering, Kanagawa University, Japan.

It has been published in Advances in Applied Probability [17] and in the invited session of the 25th conference EURO 2012 [27]

5.3. Approximation of Infinite Horizon Discounted Cost Markov Decision Processes

Participant: François Dufour.

Markov decision processes, infinite horizon discounted cost criterion, approximation and discretization

In this work, we deal with a discrete-time infinite horizon Markov decision process with locally compact Borel state and action spaces, and possibly unbounded cost function. Based on Lipschitz continuity of the elements of the control model, we propose a state and action discretization procedure for approximating the optimal value function and an optimal policy of the original control model. We provide explicit bounds on the approximation errors.

These results have been obtained in collaboration with Tomas Prieto-Rumeau, Department of Statistics and Operations Research, UNED, Madrid, Spain.

It has been published in the book Optimization, Control, and Applications of Stochastic Systems. In Honor of Onésimo Hernandez-Lerma [52].

5.4. Continuous Control of Piecewise Deterministic Markov Processes with Long Run Average Cost

Participant: François Dufour.

Piecewise-deterministic Markov Processes, long-run average cost, optimal control, integro-differential optimality equation

The main goal of this work is to derive sufficient conditions for the existence of an optimal control strategy for the long run average continuous control problem of piecewise deterministic Markov processes (PDMP's) taking values in a general Borel space and with compact action space depending on the state variable. In order to do that we apply the so-called vanishing discount approach to obtain a solution to an average cost optimality inequality (ACOI) associated to the long run average cost problem. Our main assumptions are written in terms of some integro-differential inequalities related to the so-called expected growth condition, and geometric convergence of the post-jump location kernel associated to the PDMP.

These results have been obtained in collaboration with Oswaldo Luis Do Valle Costa from Escola Politécnica da Universidade de São Paulo, Brazil.

It has been published in the book Stochastic Processes, Finance and Control. A Festschrift in Honor of Robert J. Elliott [51].

5.5. Optimal stopping for partially observed piecewise-deterministic Markov processes

Participants: Adrien Brandejsky, Benoîte de Saporta, François Dufour.

We have investigated an optimal stopping problem under partial observation for piecewise-deterministic Markov processes (PDMP) both from the theoretical and numerical points of view. PDMP's have been introduced by Davis [73] as a general class of stochastic models. They form a family of Markov processes involving deterministic motion punctuated by random jumps. One important property of a PDMP, relevant for the approach developed in this paper, is that its distribution is completely characterized by the embedded discrete time Markov chain $(Z_n, S_n)_{n\in\mathbb{N}}$ where Z_n is the n-th post-jump location and S_n is the n-th inter-jump time. We consider the following optimal stopping problem for a partially observed PDMP $(X_t)_{t\geq 0}$. Roughly speaking, the observation process $(Y_t)_{t\geq 0}$ is a point process defined through the embedded discrete time Markov chain $(Z_n, S_n)_{n\in\mathbb{N}}$. The inter-arrival times are given by $(S_n)_{n\in\mathbb{N}}$ and the marks by a noisy function of $(Z_n)_{n\in\mathbb{N}}$. For a given reward function g and a computation horizon $N \in \mathbb{N}$, we study the following optimal stopping problem

$$\sup_{\sigma \leq T_N} \mathbb{E}\left[g(X_\sigma)\right],$$

where T_N is the N-th jump time of the PDMP $(X_t)_{t\geq 0}$, σ is a stopping time with respect to the natural filtration $\mathcal{F}^o = (\mathcal{F}^o_t)_{t\geq 0}$ generated by the observations $(Y_t)_{t\geq 0}$.

A general methodology to solve such a problem is to split it into two sub-problems. The first one consists in deriving the filter process given by the conditional expectation of X_t with respect to the observed information $\mathcal{F}^o_t$. Its main objective is to transform the initial problem into a completely observed optimal stopping problem where the new state variable is the filter process. The second step consists in solving this reformulated problem, the new difficulty being its infinite dimension. Indeed, the filter process takes values in a set of probability measures.

Our work is inspired by [92] which deals with an optimal stopping problem under partial observation for a Markov chain with finite state space. The authors study the optimal filtering and convert their original problem into a standard optimal stopping problem for a continuous state space Markov chain. Then they propose a discretization method based on a quantization technique to approximate the value function. However, their method cannot be directly applied to our problem for the following main reasons related to the specificities of PDMPs.

Firstly, PDMPs are continuous time processes. Then, it appears natural to work with the embedded Markov chain $(Z_n, S_n)_{n\in\mathbb{N}}$. In addition, we assume that $(Z_n)_{n\in\mathbb{N}}$ takes finitely many values. However, an important difficulty is that the structure of stopping time remains intrinsically continuous. Consequently, our problem cannot be converted into a fully discrete time problem.

Secondly, the distribution of a PDMP combines both absolutely continuous and singular components. This is due to the existence of forced jumps when the process hits the boundary of the state space. As a consequence the derivation of the filter process is not straightforward. In particular, the absolute continuity hypothesis **(H)** of [92] does not hold.

Thirdly, in our context the reformulated optimization problem is not standard, unlike in [92]. Indeed, although we obtain a reformulation similar to an optimal stopping problem for a fully observed PDMP, it involves the Markov chain $(\Pi_n, S_n)_{n\in\mathbb{N}}$ that is not the embedded Markov chain of some PDMP. Therefore, a new derivation of dynamic programming equations is required as we cannot use the results of [81]. In particular, one needs to derive fine properties of the structure of the $(\mathcal{F}^o_t)_{t\geq 0}$-stopping times. Moreover, we construct an ϵ-optimal stopping time.

Finally, a natural way to proceed with the numerical approximation is then to follow the ideas developed in [92] [8] namely to replace the filter Π_n and the inter-jump time S_n by some finite state space approximations in the dynamic programming equation. However, a noticeable difference from [8] lies in the fact that the dynamic programming operators therein were Lipschitz continuous whereas our new operators are only Lipschitz continuous between some points of discontinuity. We overcome this drawback by splitting the operators into their restrictions onto their continuity sets. This way, we obtain not only an approximation of the value function of the optimal stopping problem but also an ϵ-optimal stopping time with respect to the filtration $(\mathcal{F}^o_t)_{t\geq 0}$ that can be computed in practice.

This work is submitted for publication [60] and presented in an invited international conference [26].

5.6. Predictive maintenance for the heated hold-up tank

Participants: Benoîte de Saporta, François Dufour, Huilong Zhang.

A complex system is inherently sensitive to failures of its components. One must therefore determine maintenance policies in order to maintain an acceptable operating condition. Optimizing the maintenance is a very important problem in the analysis of complex systems. It determines when it is best that maintenance tasks should be performed on the system in order to optimize a cost function: either maximize a performance function or conversely minimize a loss function. Moreover, this optimization must take into account the random nature of failures and random evolution and dynamics of the system.

The example considered here is the maintenance of the heated hold-up tank, a well know test case for dynamic reliability, see e.g. [75], [89], [90], [94]. The system consists of a tank containing a fluid whose level is controlled by three components: two inlet pumps and one outlet valve. A thermal power source heats up the fluid. The failure rate of the components depends on the temperature, the position of the three components monitors the liquid level in the tank, and in turn, the liquid level determines the temperature. The main characteristic of this system is that it can be modeled by a stochastic hybrid process, where the discrete and continuous parts interact in a closed loop. As a consequence, simulating this process and computing related reliability indices has been a challenge for the dynamic reliability community. To our best knowledge, optimization of maintenance policies for the heated hold-up tank has not been addressed yet in the literature.

The only maintenance operation considered here is the complete replacement of all the failed components and the system restarts in its initial equilibrium state. Partial repairs are not allowed. Mathematically, this problem of preventive maintenance corresponds to a stochastic optimal stopping problem as explained by example in the book of Aven and Jensen [68]. It is a difficult problem because of the closed loop interactions between the state of the components and the liquid level and temperature. A classical approach consists in using condition-based maintenance (CBM) to act on the system based on its current state and before its failure. One can for example calculate the remaining useful life (RUL) of the system and the preventive replacement is carried out when the deterioration level exceeds a certain threshold or enters in a certain state [96], [80]. Our approach also takes into account the current state of the process, but our decision rule is not based on damage accumulation nor does it correspond to hitting some threshold. Instead, it involves a performance function that reflects that the longer the system is in a functioning state the better.

The dynamics of the heated hold-up tank can be modeled by a piecewise deterministic Markov process (PDMP), see [94]. Therefore, our maintenance problem boils down to an optimal stopping problem for PDMP's. PDMP's are a class of stochastic hybrid processes that has been introduced by Davis [73] in the 80's. These processes have two components: a Euclidean component that represents the physical system (e.g. temperature, pressure, ...) and a discrete component that describes its regime of operation and/or its environment. Starting from a state x and mode m at the initial time, the process follows a deterministic trajectory given by the laws of physics until a jump time that can be either random (e.g. it corresponds to a component failure or a change of environment) or deterministic (when a magnitude reaches a certain physical threshold, for example the pressure reaches a critical value that triggers a valve). The process restarts from a new state and a new mode of operation, and so on. This defines a Markov process. Such processes can naturally take into account the dynamic and uncertain aspects of the evolution of the system. A subclass of these processes has been introduced by Devooght [75] for an application in the nuclear field. The general model has been introduced in dynamic reliability by Dutuit and Dufour [79].

As illustrated above, it is crucial to have an efficient numerical tool to compute the optimal maintenance time in practical cases. To this aim, a general numerical approach was developed in [8]. It was first applied to an example of maintenance of a metallic structure subject to corrosion, without closed loop interactions or deterministic jumps, and with a simple cost function that did not depend on time, see [23]. The objective of the present paper is to further demonstrate the high practical power of the theoretical methodology described in [8], by applying it to the more challenging heated hold-up tank problem. The cost function chosen here is also more complex as it takes into account both continuous components as well as the running time. More precisely, we propose to compute the optimal cost as well as a quasi-optimal stopping rule, which is the date when the maintenance should be performed. As a by-product of our procedure, the distribution of the optimal maintenance dates is also obtained, as well as the distributions of the liquid level and temperature at the chosen maintenance date.

This work is submitted for publication [66] and presented in an international conference [32].

5.7. Efficient simulation of the availability of a feedwater control system

Participants: Benoîte de Saporta, François Dufour, Huilong Zhang.

In the reliability modeling of complex control systems, classical methodologies such as even-trees/fault-trees or Petri nets may not represent adequately the dynamic interactions existing between the physical processes (modeled by continuous variables) and the functional and dysfunctional behavior of its components (modeled by discrete variables). We have proposed a framework for modeling and simulation of a water level control system in the steam generator (SG) in the secondary circuit of a nuclear power plant. A similar benchmark system was described by the U.S. Nuclear Regulatory Commission [67] to compare two approaches to dynamic reliability: DFM (Dynamic Flowgraph Methodology) and Markov/CCMT (Cell-to-Cell Mapping Technique). But the report released by the NRC is not sufficient to reconstruct a realistic model. We have developed a complete benchmark case. The behavioral model of SG is obtained from a linearized model published in 2000 by EDF [87]. Detailed description of the components, failure modes and control laws of the principal components is presented. For modeling the system, we use the piecewise deterministic Markov processes (PDP) framework [73] and for implementation we chose Simulink associated with Stateflow. PDP's offer a very general modeling framework to deal with dynamic reliability problems; Simulink is a good tool to simulate non linear differential equations and their controller, while Stateflow implementation is appropriate for finite state machine descriptions of different components.

In our benchmark system, four physical processes are considered: feedwater flowrate, steam flow, narrow range water level and wide range water level. A PID controller is used to maintain the water level within limits of set-points. The system is composed of seven components: 1 passive system representing vapor transport system, 3 extraction pumps, 2 feeding turbopumps, and 1 waterflow regulation valve. The functional and dysfunctional behaviors and the failure rates of each component are based on operational experience. In 2012, we have further improved our simulator by taking captors (and their possible failures) into account.

This work was presented in an international conference [36], a national conference [39] and is published as a book chapter [49].

5.8. Stochastic control for underwater optimal trajectories

Participants: Benoîte de Saporta, François Dufour, Huilong Zhang.

This work aims to compute optimal trajectories for underwater vehicles evolving in a given environment to accomplish some tasks. This is an optimal control problem. In real context, available inputs are not perfectly known. Hence a stochastic approach seems to be needed. Markov decision processes (MDPs) constitute a general family of controlled stochastic processes suitable for the modeling of sequential decision-making problems. The analysis of MDPs leads to mathematical and computational problems. The corresponding theory has reached a rather high degree of maturity, although the classical tools (such as value iteration, policy iteration, linear programming, and their various extensions) are generally hardly applicable in practice. Hence, solving MDPs numerically is an awkward and important problem. The method is applied to control a submarine which wants to well detect one or several targets. Why? A smart operator, if provided information about target's position and velocity and a sound propagation code can find a good trajectory. If we- now consider a submarine surrounded by several targets, it is clear that a human operator will have great difficulty to find the best route.

This work was presented in an international conference [35].

5.9. Statistical study od asymmetry in cell lineage data

Participants: Benoîte de Saporta, Anne Gégout-Petit.

This work proposes a rigorous methodology to study cell division data consisting in several observed genealogical trees of possibly different shapes. For instance, [93] filmed 94 colonies of Escherichia coli cells dividing between four and nine times. We propose a new rigorous approach to take into account all the available information. Indeed, we propose an inference based on a finite fixed number of replicated trees when the total number of observed cells tends to infinity. We use the missing data asymmetric BAR model introduced by [7]. In this approach, the observed genealogies are modeled with a two-type Galton Watson (GW) process. However, we propose a different least-squares estimator for the parameters of the BAR process

that does not correspond to the single-tree estimators averaged on the replicated trees. We also propose an estimator of the parameters of the GW process specific to our binary tree structure and not based simply on the observation of the number of cells of each type in each generation.

Our procedure allows us to fully take into account missing observations, data from different trees as well as the dependence structure within genealogical trees. It also enables us to use all the information available without the drawbacks of low accuracy for estimators or low power for tests on small single trees. We study the consistency and asymptotic normality of our estimators and derive asymptotic confidence intervals as well as Wald's type tests to investigate the asymmetry of the data for both the BAR and GW processes. Our results are applied to the Escherichia coli data of [93].

This work is in collaboration with Laurence Marsalle (Lille 1 University). It is submitted for publication [65] and was presented in an international conference [33].

5.10. Random coefficient bifurcating autoregressive processes

Participants: Benoîte de Saporta, Anne Gégout-Petit.

In the 80's, Cowan and Staudte [72] introduced Bifurcating Autoregressive processes (BAR) as a parametric model to study cell lineage data. A quantitative characteristic of the cells (e.g. growth rate, age at division) is recorded over several generations descended from an initial cell, keeping track of the genealogy to study inherited effects. As a cell usually gives birth to two offspring by division, such genealogies are naturally structured as binary trees. BAR processes are thus a generalization of autoregressive processes (AR) to this binary tree structure, by modeling each line of descent as a first order AR process, allowing the environmental effects on sister cells to be correlated. Statistical inference for the parameters of BAR processes has been widely studied, either based on the observation of a single tree growing to infinity [72], [85], [83], [95] or on a large number of small independent trees [86], [84].

Various extensions of the original model have been proposed, but to our best knowledge, only two papers [71] and [70] deal with random coefficient BAR processes. In the former by Bui and Huggins it is explained that random coefficients BAR processes can account for observations that do not fit the usual BAR model. For instance, the extra randomness can model irregularities in nutrient concentrations in the media in which the cells are grown. In this work, we propose a new model for random coefficient BAR processes (R-BAR). It is more general than that of Bui and Huggins, as the random variables are not supposed to be Gaussian, they may not have moments of all order and correlation between all the sources of randomness are allowed. Moreover, we propose an asymmetric model in the continuance of [82], [69], [74], [70], [7], [24] in the context of missing data. Indeed, experimental data are often incomplete and it is important to take this phenomenon into account for the inference. We model the structure of available data by a Galton Watson tree, instead of a complete binary tree. Our model is close to that developed in [70], but the assumptions on the noise process are different as we allow correlation between the two sources of randomness but require higher moments because of the missing data and because we do not use a weighted estimator. The main difference is that the model in [70] is fully observed, whereas ours allows for missing observations.

Our approach for the inference of our model is also different from [71], [70]. As we cannot use maximum likelihood estimation, we propose modified least squares estimators as in [91]. The originality of our approach is that it combines the bifurcating Markov chain and martingale approaches. Bifurcating Markov chains (BMC) were introduced in [82] on complete binary trees and further developed in [74] in the context of missing data on Galton Watson trees. BAR models can be seen as a special case of BMC. This interpretation allows us to establish the convergence of our estimators. A by-product of our procedure is a new general result for BMC on Galton Watson trees. Indeed, in [82], [74] the driven noise sequence is assumed to have moments of all order. Here, we establish new laws of large numbers for polynomial functions of the BMC where the noise sequence only has moments up to a given order. The strong law of large numbers [78] and the central limit theorem for martingales have been previously used in the context of BAR processes and adapted to special cases of martingales on binary trees. In this paper, we establish a general law of large numbers for square integrable martingales on Galton Watson binary trees. This result is applied to our R-BAR model to obtain sharp convergence rates and a quadratic strong law for our estimators.

This work is in collaboration with Laurence Marsalle (Lille 1 University). It is submitted for publication [64].

5.11. Hidden Markov Model for the detection of a degraded state in an optronic equipment

Participants: Camille Baysse, Anne Gégout-Petit, Jérôme Saracco.

As part of optimizing the reliability, Thales Optronics now includes systems that examine the state of its equipment. This function is performed by HUMS (Health & Usage Monitoring System). We hope to implement a program based on these observations that can determine the lifetime of this optronic equipment. Our study focuses on a simple example of HUMS. As part of our research, we are interested in a variable called "time-to cold" noted TMF, which reflects the state of system. Using this information about this variable, we seek to detect as soon as possible a degraded state and propose maintenance before failure. For this we use a hidden Markov model. The state of our system at time t is then modeled by a Markov chain X_t. However we do not observe directly this chain but indirectly through the TMF, a noisy function of this chain. Thanks to filtering equations, we obtained results on the probability that an equipment breaking down at time t, knowing the history of the TMF until this moment. We have subsequently studied this methodology with simulated data. Then finally we applied these results on the analysis of our real data and we have checked that the results are consistent with the reality. So using this method could allow the company to recall equipments which are estimated in deteriorated state and do not control those estimated in stable state. Thales Optronics could improve its maintenance system and reduce its cost function.

This work is a part of the CIFRE PhD of Camille Baysse also supervised for the Thales part by Didier Bihannic and Michel Prenat. It was presented in an national conference [38] and is submitted for publication in an national per-reviewed journal [58].

5.12. Predictive maintenance for an optronic equipment

Participants: Camille Baysse, Benoîte de Saporta, Anne Gégout-Petit, Jérôme Sarraco.

After the problem of detection of a degraded state, we have tackled the problem of predictive maintenance for an optronic equipment. For this we model the state of the system by a PDMP (state with three possible values and cumulative time of use). In this framework, we reformulate the problem of maintenance of optimization in an optimal stopping problem maximizing a criteria about time of use without failure. In this framework, we can use known results developed in the CQFD team on optimal control [8], [23]. We have extensively studied the problem with simulated data, computed grid of quantization and optimal policy for the real problem. This results will be implemented by Thales in HUMS of optronic equipment.

This work was presented in an national conference [38] and an abstract is accepted for publication in an international conference with papers.

5.13. Non parametric estimation of the jump rate for non-homogeneous marked renewal processes

Participants: Romain Azaïs, François Dufour, Anne Gégout-Petit.

This work is devoted to the nonparametric estimation of the jump rate and the cumulative rate for a general class of non-homogeneous marked renewal processes, defined on a separable metric space. In our framework, the estimation needs only one observation of the process within a long time. Our approach is based on a generalization of the multiplicative intensity model, introduced by Aalen in the seventies. We provide consistent estimators of these two functions, under some assumptions related to the ergodicity of an embedded chain and the characteristics of the process. The methodology is illustrated by a numerical example. It is the object of a paper [57] to appear in the Annales de l'Intitut Poincaré

5.14. Non parametric estimation of conditional distribution of the interjumping times for piecewise Markov processes

Participants: Romain Azaïs, François Dufour, Anne Gégout-Petit.

This work gives a nonparametric method for estimating the conditional density associated to the jump rate of a piecewise-deterministic Markov process. In our framework, the estimation needs only one observation of the process within a long time interval. Our method relies on a generalization of Aalen's multiplicative intensity model. We prove the uniform consistency of our estimator, under some reasonable assumptions related to the primitive characteristics of the process. A simulation example illustrates the behavior of our estimator. This work is the object of a paper [56] submitted for publication

5.15. Stochastic modelling and simulation of fatigue crack propagation using piecewise-deterministic Markov processes

Participants: Romain Azaïs, Anne Gégout-Petit.

Fatigue crack propagation is a stochastic phenomenon in nature due to the inherent uncertainties coming from material properties, environmental conditions and loads. Stochastic processes offer an appropriate framework for modelling crack propagation since it is intended to include sources variabilities. In this work, we propose to model crack propagation mechanism with Piecewise Deterministic Markov Process (PDMP) using usual random crack laws. Conventional laws proposed in the literature seem inadequate for describing the whole fatigue crack trajectory mainly when the crack extends in a rapid manner. To overcome this drawback, a new modelling is proposed that consists in using more than one law as each one is more suitable for a specific phase during crack propagation. Regime-switching models seem very attractive and with our modelling assessed crack growth rates and crack lengths are very close to experimental values. Moreover, behaviour just before failure is well captured and can be discussed. Empirical curves from literature are used to adjust the parameters associated to the proposed modelling. Statistical observations and numerical simulations show the efficiency of the proposed approach to model and to simulate fatigue crack growth. This work has been presented in an international congress [34] and is the object of a paper which will be submitted very soon.

5.16. Statistical Analysis of Grapevine Mortality Associated with Esca or Eutypa Dieback Foliar Expression

Participant: Anne Gégout-Petit.

Esca and Eutypa dieback are two major wood diseases of grapevine in France. Their widespread distribution in vineyards leads to vine decline and to a loss in productivity. However, little is known either about the temporal dynamics of these diseases at plant level, and equally, the relationships between foliar expression of the diseases and vine death is relatively unknown too. . To investigate these questions, we surveyed the vines of six vineyards cv. Cabernet Sauvignon in the Bordeaux region, by recording foliar symptoms, dead arms and dead plants from 2004 to 2010. In 2008, 2009 and 2010, approximately five percent of the asymptomatic vines died but the percentage of dead vines which had previously expressed esca foliar symptoms was higher, and varied between vineyards. A logistic regression model was used to select the previous years of symptomatic expression associated with vine mortality. The mortality of esca is always associated with the foliar symptom expression of the year preceding vine death. One or two other earlier years of expression frequently represented additional risk factors. The Eutypa dieback symptom was also a risk factor of death, superior or equal to that of esca. The study of the internal necroses of vines expressing esca or Eutypa dieback is discussed in the light of these statistical results. This work has been presented in an international congress [44] and is the object of a submitted paper.

5.17. MonteCarlo test for two patterns of point processes on a grid

Participants: Anne Gégout-Petit, Marie Chavent, Amaury Labenne.

In order to compare two patterns of distribution of symptomatic or dead vines in a same vineyard but for two consecutive years, we have developed a Monte Carlo test. First we estimate the intensity of occurrence of disease in one of the pattern, then we simulate n realizations i.i.d. of this intensity and compute the associate likelihoods in order to build an interval that cover $(1-\alpha)$ per cent of the realizations. The test reject the equality of repartition if the likelihood computed with the second pattern is not included in this interval. We have made simulations and applied this test to the repartition of esca in vineyard. This work has been presented in a national workshop on software R [46].

5.18. Multivariate Analysis for the detection of the effect of a treatment

Participant: Anne Gégout-Petit.

The aim of this work is to give some statistical rules to determine if a patient is meeting a given treatment (a BD here). The criterium commonly used to determine if a patient is meeting a BD treatment is based only on one physiological parameter : if this parameter increases, the patient is meeting. But now, many physiological parameters are measured in routine and it seems that a patient could have a global amelioration of his health state due to the treatment without an increase of the single used parameter.

Using standard multivariate analysis techniques, and classification, we have proposed criteria to discriminate groups of patients different in regard of their response to treatment. This work will be used by physiologists to propose new criteria for the measure of the effect of a BD treatment. It is in collaboration with physiologists from Bordeaux and Nantes universities and is the object of a submitted paper in a international peer-reviewed journal in the domain of pneumology .

5.19. A hidden renewal model for monitoring aquatic systems biosensors

Participants: Romain Azaïs, Raphaël Coudret.

This work aims at modeling signals of oysters' openings over time using a four-state renewal process. Two of them are of particular interest and correspond to instants when the animals are open or closed. An estimator of the cumulative jump rate of this process is provided. It relies on observations of the jumps between the four states. Here these measures are not available but the observed signal takes ranges of real values according to this underlying process. A procedure to estimate a probability density function that summarizes the information of the signal is explained. This leads to estimate the hidden renewal process and then its cumulative jump rate for each oyster. A classification of these functions for a group of oysters discriminate them according to their assumed health status. Such a diagnosis is essential when using these animals as biosensors for water quality assessment. This work is a joint work with Gilles Durrieu from Université de Bretagne Sud and in collaboration with UMR CNRS 5805 EPOC.

5.20. A recursive nonparametric estimator for the transition kernel of a piecewise-deterministic Markov process

Participant: Romain Azaïs.

We investigate a nonparametric approach to provide a recursive estimator of the transition density of a non-stationary piecewise-deterministic Markov process, from only one observation of the path within a long time. In this framework, we do not observe a Markov chain with transition kernel of interest. Fortunately, one may write the transition density of interest as the ratio of the invariant distributions of two embedded chains of the process. Our method consists in estimating these invariant measures. We state a result of consistency under some general assumptions about the main features of the process. A simulation study illustrates the well asymptotic behavior of our estimator. This work is the object of a paper [55] submitted for publication.

5.21. A new sliced inverse regression method for multivariate response

Participants: Jérôme Saracco, Raphaël Coudret.

We consider a semiparametric regression model of a q-dimensional multivariate response y on a p-dimensional covariate x. In this paper, a new approach is proposed based on sliced inverse regression for estimating the e ffective dimension reduction (EDR) space without requiring a prespeci ed parametric model. The convergence at rate square root of n of the estimated EDR space is shown. We discuss the choice of the dimension of the EDR space. The numerical performance of the proposed multivariate SIR method is illustrated on a simulation study. Moreover, we provide a way to cluster components of y related to the same EDR space. One can thus apply properly multivariate SIR on each cluster instead of blindly applying multivariate SIR on all components of y. An application to hyperspectral data is provided.

These results have been obtained in collaboration with Stéphane Girard (Inria Rhône Alpes).

The paper is under revision for possible publication in CSDA [63].

5.22. Comparison of kernel density estimators with assumption on number of modes

Participants: Jérôme Saracco, Raphaël Coudret.

A data-driven bandwidth choice for a kernel density estimator called critical bandwidth is investigated. This procedure allows the estimation to have as many modes as assumed for the density to estimate. Both Gaussian and uniform kernels are considered. For the Gaussian kernel, asymptotic results are given. For the uniform kernel, an argument against these properties is mentioned. These theoretical results are illustrated with a simulation study which compare the kernel estimators that rely on critical bandwidth with another one which uses a plug-in method to select its bandwidth. An estimator that consists in estimates of density contour clusters and takes assumptions on number of modes into account is also considered. Finally, the methodology is illustrated using environment monitoring data.

These results have been obtained in collaboration with Gilles Durrieu (Université Bretagne-Sud).

The paper is under revision for possible publication in Communications in Statistics - Simulation and Computation [62].

5.23. A new approach on recursive and non-recursive SIR methods

Participant: Jérôme Saracco.

We consider a semiparametric single index regression model involving a p-dimensional quantitative covariable x and a real dependent variable y. A dimension reduction is included in this model via an index $x'\beta$. Sliced inverse regression (SIR) is a well-known method to estimate the direction of the Euclidean parameter β which is based on a "slicing step" of y in the population and sample versions. The goal of this paper is twofold. On the one hand, we focus on a recursive version of SIR which is also suitable for multiple indices model. On the other hand, we propose a new method called SIRoneslice when the regression model is a single index model. The SIRoneslice estimator of the direction of β is based on the use of only one "optimal" slice chosen among the H slices. Then, we provide its recursive version.We give an asymptotic result for the SIRoneslice approach. Simulation study shows good numerical performances of the SIRoneslice method and clearly exhibits the main advantage of using recursive versions of the SIR and SIRoneslice methods from a computational time point of view. A real dataset is also used to illustrate the approach. Some extensions are discussed in concluding remarks. The proposed methods and criterion have been implemented in R and the corresponding codes are available from the authors.

These results have been obtained in collaboration with Bernad Bercu (Université Bordeaux 1) and Thi Mong Ngoc Nguyen (Université de Strasbourg).

The paper has been published in the Journal of the Korean Statistical Society [11].

5.24. On the asymptotic behavior of the Nadaraya-Watson estimator associated with the recursive SIR method

Participant: Jérôme Saracco.

We investigate the asymptotic behavior of the Nadaraya-Watson estimator for the estimation of the regression function in a semiparametric regression model. On the one hand, we make use of the recursive version of the sliced inverse regression method for the estimation of the unknown parameter of the model. On the other hand, we implement a recursive Nadaraya-Watson procedure for the estimation of the regression function which takes into account the previous estimation of the parameter of the semiparametric regression model.We establish the almost sure convergence as well as the asymptotic normality for our Nadaraya-Watson estimator. We also illustrate our semiparametric estimation procedure on simulated data.

These results have been obtained in collaboration with Bernad Bercu (Université Bordeaux 1) and Thi Mong Ngoc Nguyen (Université de Strasbourg) .

The paper is submitted [59].

5.25. Comparison of sliced inverse regression approaches for underdetermined cases

Participants: Jérôme Saracco, Raphaël Coudret.

Among methods to analyze high-dimensional data, the sliced inverse regression (SIR) is of particular interest for non-linear relations between the dependent variable and some indices of the covariate. When the dimension of the covariate is greater than the number of observations, classical versions of SIR cannot be applied. Various upgrades were then proposed to tackle this issue such as RSIR and SR-SIR, to estimate the parameters of the underlying model and to select variables of interest. In this paper, we introduce two new estimation methods respectively based on the QZ algorithm and on the Moore-Penrose pseudo-inverse. We also describe a new selection procedure of the most relevant components of the covariate that relies on a proximity criterion between submodels and the initial one. These approaches are compared with RSIR and SR-SIR in a simulation study. Finally we applied SIR-QZ and the associated selection procedure to a genetic dataset in order to find eQTL.

These results have been obtained in collaboration with Benoit Liquet (Université Bordeaux 2) . The paper is submitted .

5.26. Orthogonal rotation in PCAMIX

Participants: Marie Chavent, Jérôme Saracco.

Kiers (1991) considered the orthogonal rotation in PCAMIX, a principal component method for a mixture of qualitative and quantitative variables. PCAMIX includes the ordinary Principal Component Analysis (PCA) and Multiple Correspondence Analysis (MCA) as special cases. In this work, we give a new presentation of PCAMIX where the principal components and the squared loadings are obtained from a Singular Value Decomposition. The loadings of the quantitative variables and the principal coordinates of the categories of the qualitative variables are also obtained directly. In this context, we propose a computationaly efficient procedure for varimax rotation in PCAMIX and a direct solution for the optimal angle of rotation. A simulation study shows the good computational behavior of the proposed algorithm. An application on a real data set illustrates the interest of using rotation in MCA. All source codes are available in the R package “PCAmixdata”.

These results have been obtained in collaboration with Vanessa Kuentz of IRSTEA (UR ABDX).

It has been published in Advances in Data Analysis and Classification [15] and presented in the context of application in cultural sociology in the Premières Rencontres R [42].

5.27. A sliced inverse regression approach for data stream

Participants: Marie Chavent, Jérôme Saracco.

In this work, we focus on data arriving sequentially by block in a stream. A semiparametric regression model involving a common EDR (Effective Dimension Reduction) direction is assumed in each block. Our goal is to estimate this direction at each arrival of a new block. A simple direct approach consists in pooling all the observed blocks and estimate the EDR direction by the SIR (Sliced Inverse Regression) method. But some disadvantages appear in practice such as the storage of the blocks and the running time for high dimensional data. To overcome these drawbacks, we propose an adaptive SIR estimator of based on the SIR approach for a stratified population developed by Chavent et al. (2011). The proposed approach is faster both from computational complexity and running time points of view, and provides data storage benefits. We show the consistency of our estimator at the root-n rate and give its asymptotic distribution. We propose an extension to multiple indices model. We also provide a graphical tool in order to detect if a drift occurs in the EDR direction or if some aberrant blocks appear in the data stream. In a simulation study, we illustrate the good numerical behavior of our estimator. One important advantage of this approach is its adaptability to changes in the underlying model. Finally we apply it on real data concerning the estimation of Mars surface physical properties.

This work is under revision in Statistics and Computing [61].

5.28. ClustOfVar: An R Package for the Clustering of Variables

Participants: Marie Chavent, Jérôme Saracco.

Clustering of variables is as a way to arrange variables into homogeneous clusters, i.e., groups of variables which are strongly related to each other and thus bring the same information. These approaches can then be useful for dimension reduction and variable selection. Several specific methods have been developed for the clustering of numerical variables. However concerning qualitative variables or mixtures of quantitative and qualitative variables, far fewer methods have been proposed. The R package ClustOfVar was specifically developed for this purpose. The homogeneity criterion of a cluster is defined as the sum of correlation ratios (for qualitative variables) and squared correlations (for quantitative variables) to a synthetic quantitative variable, summarizing "as good as possible" the variables in the cluster. This synthetic variable is the first principal component obtained with the PCAMIX method. Two clustering algorithms are proposed to optimize the homogeneity criterion: iterative relocation algorithm and ascendant hierarchical clustering. We also propose a bootstrap approach in order to determine suitable numbers of clusters. We illustrate the methodologies and the associated package on small datasets.

These results have been obtained in collaboration with Vanessa Kuentz of IRSTEA (UR ABDX).

It has been published in Journal of Statistical Softwares [14]. The study of the inclusion of environment by the farmer with ClustOfVar has been presented in the Premières Rencontres R and in [45]

5.29. Divisive Monothetic Clustering for Interval and Histogram-valued Data

Participant: Marie Chavent.

In this paper we propose a divisive top-down clustering method designed for interval and histogram-valued data. The method provides a hierarchy on a set of objects together with a monothetic characterization of each formed cluster. At each step, a cluster is split so as to minimize intra-cluster dispersion, which is measured using a distance suitable for the considered variable types. The criterion is minimized across the bipartitions induced by a set of binary questions. Since interval-valued variables may be considered a special case of histogram-valued variables, the method applies to data described by either kind of variables, or by variables of both types. An example illustrates the proposed approach.

These results have been obtained in collaboration with Paula Brito of Porto University and presented in ICPRAM'2012 [31].

5.30. Classification of EEG signals by an evolutionary algorithm

Participants: Marie Chavent, Laurent Vézard.

The goal is to predict the alertness of an individual by analyzing the brain activity through electroencephalographic data (EEG) captured with 58 electrodes. Alertness is characterized as a binary variable that can be in a normal or relaxed state. We collected data from 44 subjects before and after a relaxation practice, giving a total of 88 records. After a pre-processing step and data validation, we analyzed each record and discriminate the alertness states using our proposed slope criterion. Afterwards, several common methods for supervised classification (k nearest neighbors, decision trees -CART-, random forests, PLS and discriminant sparse PLS) were applied as predictors for the state of alertness of each subject. The proposed slope criterion was further refined using a genetic algorithm to select the most important EEG electrodes in terms of classification accuracy. Results shown that the proposed strategy derives accurate predictive models of alertness.

These results have been obtained in collaboration with Pierrick Legrand of ALEA Inria team.

It has been published in Journal des Nouvelles Technologies [25] and presented in COMPSTAT 2012 [47].

5.31. Variable selection by genetic algorithm for the study of alertness states.

Participants: Marie Chavent, Laurent Vézard.

The aim of this work is to predict the state of alertness of an individual (binary variable, "normal" or "relaxed") from the study of brain activity (electroencephalographic signals EEG) collected with a limited number of electrodes. In fact, the set up of electrodes during the EEG signal acquisition is time consuming and these electrodes are correlated. In our study, the EEG of 58 participants in the two alertness states (116 records) were collected via a cap with 58 electrodes. After a data validation step based on the study of the contingent negative variation (CNV), 19 subjects were retained in the study. A CSP (Common Spacial Pattern) coupled to a linear discriminant analysis were used to build a decision rule and thus predict the alertness of the participants. A genetic algorithm was used to determine a subset of electrodes of size p '(where p' <p, where p = 58 is the number of electrodes). This presentation will present the CSP in the general framework and will introduce innovations made to this method. The genetic algorithm will be described proposed and recent results will be presented.

These results have been obtained in collaboration with Pierrick Legrand of ALEA Inria team.

It has been presented in the Journée Évolutionnaire Thématique, 23éme édition [48].

5.32. Handling Missing Values with Regularized Iterative Multiple Correspondence Analysis

Participant: Marie Chavent.

A common approach to deal with missing values in multivariate exploratory data analysis consists in minimizing the loss function over all non-missing elements. This can be achieved by EM-type algorithms where an iterative imputation of the missing values is performed during the estimation of the axes and components. This paper proposes such an algorithm, named iterative multiple correspondence analysis, to handle missing values in multiple correspondence analysis (MCA). This algorithm, based on an iterative PCA algorithm, is described and its properties are studied. We point out the over tting problem and propose a regularized version of the algorithm to overcome this major issue. Finally, performances of the regularized iterative MCA algorithm (implemented in the R-package named missMDA) are assessed from both simulations and a real dataset. Results are promising with respect to other methods such as the missing-data passive modi ed margin method, an adaptation of the missing passive method used in Gini's Homogeneity analysis framework.

It has been published in Journal of Classification [21].

GEOSTAT Project-Team

6. New Results

6.1. Multiresolution analysis and optimal inference for high resolution ocean dynamics and ocean/atmosphere fluxes

Participants: Hussein Yahia [correspondant], Véronique Garçon, Oriol Pont, Joel Sudre, Christine Provost, Antonio Turiel, Christoph Garbe, Claire Pottier, Boris Dewitte.

A $p_{CO_2}^{ocean}$ signal computed as an output from the ROMS coupled physical/biogeochemical simulation model possesses the characteristics of the presence of a multiscale organization, typical of turbulence, which can be evidenced by the computation of singularity spectra. The multiscale organization is related to the cascading properties of intensive variables acquired from the underlying system. We show how to perform inference along the scales in order to build higher resolution of $p_{CO_2}^{ocean}$ maps. Figure 4 illustrates clearly one of the main ideas implemented in this study: coherent structures of $p_{CO_2}^{ocean}$ and SST (Sea Surface Temperature) signals are related, and the LPEs, which are dimensionless quantities recording transition strengths in a signal, encode properly the multiscale transitions.

Figure 4. Local Predictability Exponents (LPEs) of ROMS-simulated $p_{CO_2}^{ocean}$ signal (left) and of corresponding SST (Sea Surface Temperature) generated signal (right). Transitions are are visually and quantitatively correlated, although not the same.

We perform a linear regression test:

$$\mathcal{S}(p_{CO_2}^{ocean})(x) = a(x)\mathcal{S}(SST)(x) + b(x)\mathcal{S}(CHLa)(x) + c(x) \quad (1)$$

with $\mathcal{S}(p_{CO_2}^{ocean})(x)$: LPE of $p_{CO_2}^{ocean}$ at x, $\mathcal{S}(SST)(x)$: LPE of SST at x, $\mathcal{S}(CHLa)(x)$: LPE of CHLa signal at x (CHLa: ocean colour data, corresponding to chlorophyl concentration). Tests are conducted over a period of 10 years on ROMS simulated data, with images corresponding to 128×128 pixels for the high resolution and 32×32 for the low resolution. There is one data every 10 days. In figure 5 we compare the functional dependencies of $p_{CO_2}^{ocean}$ vs. SST and CHLa with those of the corresponding LPEs: the original signals are physical variables of different dimensions, with complex undetermined functional dependencies. On the contrary, the dimensionless LPEs of these variables, which record the multiscale transitions, display clearly a much simpler dependency, approximated at satisfactory precision by a linear regression.

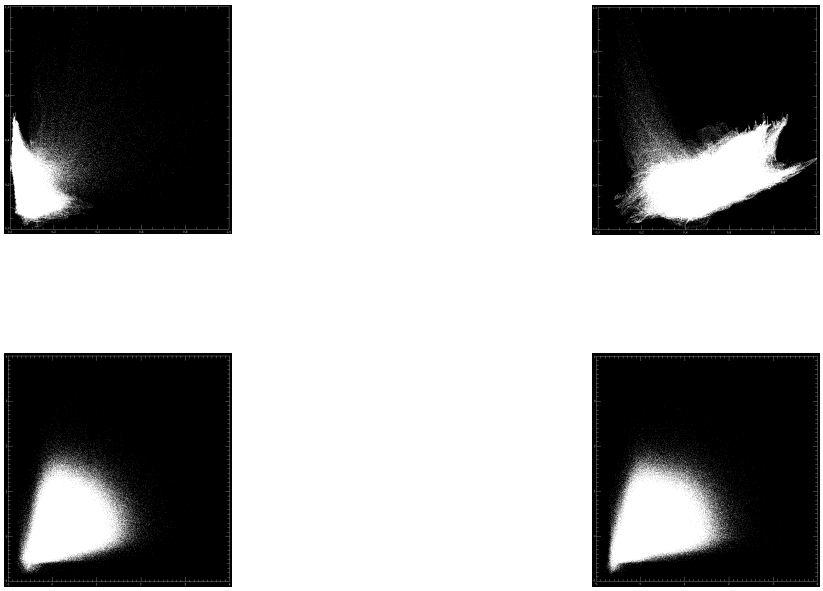


Figure 5. Pictures indicating the nature of the functional dependencies of $p_{CO_2}^{ocean}$ vs. CHLa (top left), of $p_{CO_2}^{ocean}$ vs. SST (top right), of $\mathcal{S}(p_{CO_2}^{ocean})$ vs $\mathcal{S}(CHLa)$ (bottom left) and of $\mathcal{S}(p_{CO_2}^{ocean})$ vs $\mathcal{S}(SST)$ (bottom right). The dependencies are computed on a 10-year ROMS simulation dataset, with a time frequency of one every 10 days.

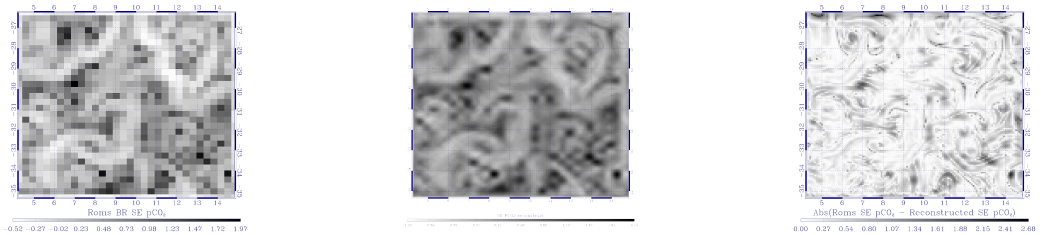


Figure 6. Left : the low resolution version of LPEs for $\mathcal{S}(p_{CO_2}^{ocean})$. Middle: result of the reconstruction. Right: absolute difference map between the ROMS generated high resolution LPEs and the reconstructed.

We prove the feasibility of a reconstruction by computing the high resolution LPEs $\mathcal{S}(p_{CO_2}^{ocean})(x)$ from their low resolution counterparts and an effective multiresolution analysis, using only an approximation of the optimal wavelet in the form of a Battle-Lemarié 3-31 mother wavelet. We show in figure 6 the results obtained by inference along the scales. The reconstructed LPEs of $p_{CO_2}^{ocean}$ are in good correspondence with the original high resolution signal.

- Related publications: [15], [16], [24], [14].

6.2. Singularity analysis and reconstructible systems

Participants: Oriol Pont [correspondant], Hussein Yahia, Antonio Turiel.

The local singularity exponents of a signal are directly related to the distribution of information in it. This fact implies that accurate evaluation of such exponents opens the door to signal reconstruction and characterisation of the dynamical parameters of the process originating the signal. Many practical implications arise in a context of digital signal processing, since the information on singularity exponents is usable for compact encoding, reconstruction and inference. The evaluation of singularity exponents in a digital context is not straightforward and requires the calculation of the Unpredictable Point Manifold of the signal. In this work, we present an algorithm for estimating the values of singularity exponents at every point of a digital signal of any dimension. We show that the key ingredient for robust and accurate reconstructibility performance lies on the definition of multiscale measures in the sense that they encode the degree of singularity and the local predictability at the same time. See figure 7 .

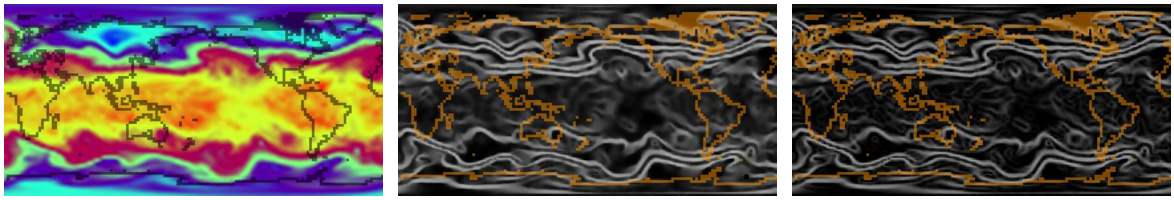


Figure 7. Left: 876576th hour slice of ERA-40 artificially rescaled 4x with bicubic interpolation for the purpose of clarity of illustration. Middle: singularity exponents calculated only in the space. Some rescaling artefacts visibly appear but without significant disturbance of the fine structure details. Right: singularity exponents calculated in the space-time domain. Notice the increased degree of detail when the temporal information is taken into account.

- Related publication: [13].

6.3. Multiscale analysis of the heart electric potential: describing atrial fibrillation

Participants: Oriol Pont [correspondant], Hussein Yahia, Rémi Dubois.

The cardiac electrical activity is a complex system, for which nonlinear signal-processing is required to characterize it properly. In this context, an analysis in terms of singularity exponents is shown to provide compact and meaningful descriptors of the structure and dynamics. In particular, singularity components reconstruct the epicardial electric potential maps of human atria, inverse-mapped from surface potentials; such approach describe sinus-rhythm dynamics as well as atrial flutter and atrial fibrillation. See figure 2 .

- Related publications: [12], [20], [23].

6.4. Edges, transitions and criticality

Participants: Suman Maji [correspondant], Hussein Yahia.

In this work, various notions of edges encountered in digital image processing are reviewed in terms of compact representation (or completion). We show that critical exponents defined in Statistical Physics lead to a much more coherent definition of edges, consistent across the scales in acquisitions of natural phenomena, such as high resolution natural images or turbulent acquisitions. Edges belong to the multiscale hierarchy of an underlying dynamics, they are understood from a statistical perspective well adapted to fit the case of natural images. Numerical computation methods for the evaluation of critical exponents in the non-ergodic case are recalled, which apply for the vast majority of natural images. We study the framework of reconstructible systems in a microcanonical formulation, show how it redefines edge completion, and how it can be used to evaluate and assess quantitatively the adequation of edges as candidates for compact representations. We study with particular attention the case of turbulent data, in which edges in the classical sense are particularly challenged. Tests are conducted and evaluated on a standard database for natural images. We test the newly introduced compact representation as an ideal candidate for evaluating turbulent cascading properties of complex images, and we show better reconstruction performance than the classical tested methods. See figure 8 .

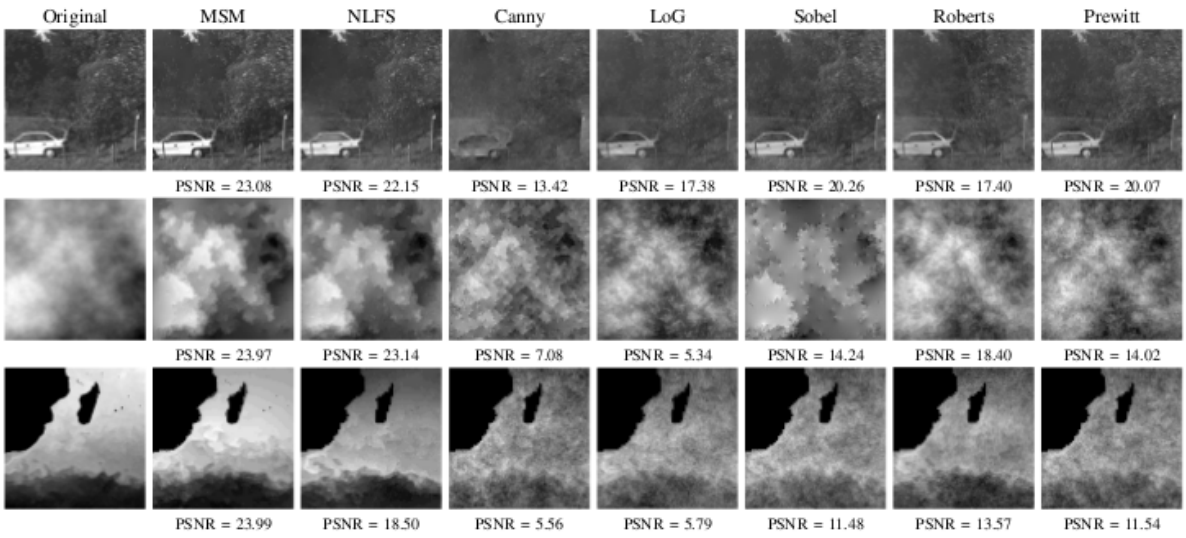


Figure 8. From left to right in each line: an original input image, and the reconstruction performed on the outputs resulting from various edge detection algorithms, showing the superiority of edge pixels computed from the Microcanonical Multiscale Formalism (column MSM). Note that NLFS [32], which is based on nonlinear filtering, performs the best after MSM.

6.5. Reconstruction of Optical phase from acquired sub-image gradients

Participants: Suman Maji [correspondant], Hussein Yahia, Thierry Fusco.

Turbulence in the Earth's atmosphere leads to a distortion in the planar wavefront from outer space resulting in a phase error. This phase error is responsible for the refractive blurring of images accounting to the loss in spatial resolution power of ground based telescopes. The common mechanism used to remove phase error from incoming wavefront is Adaptive Optics (AO). In AO systems, an estimate of the phase error is obtained from the gradient measurements of the wavefront collected by a Hartmann-Shack (HS) sensor. The correction estimate is then passed through a servo-control loop to a deformable mirror which compensates for the loss in resolution power. In this work, we propose a new approach to reconstructing the phase error from the HS

Table 1: Evaluation of the reconstructed phase under different levels of noise.

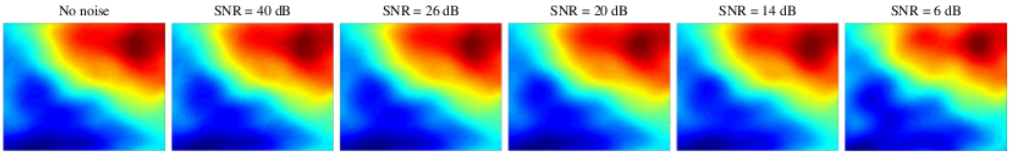


Table 2: Evaluation of the reconstructed phase using log power spectrum (**row 1**) and atmospheric structure functions (**row 2**).

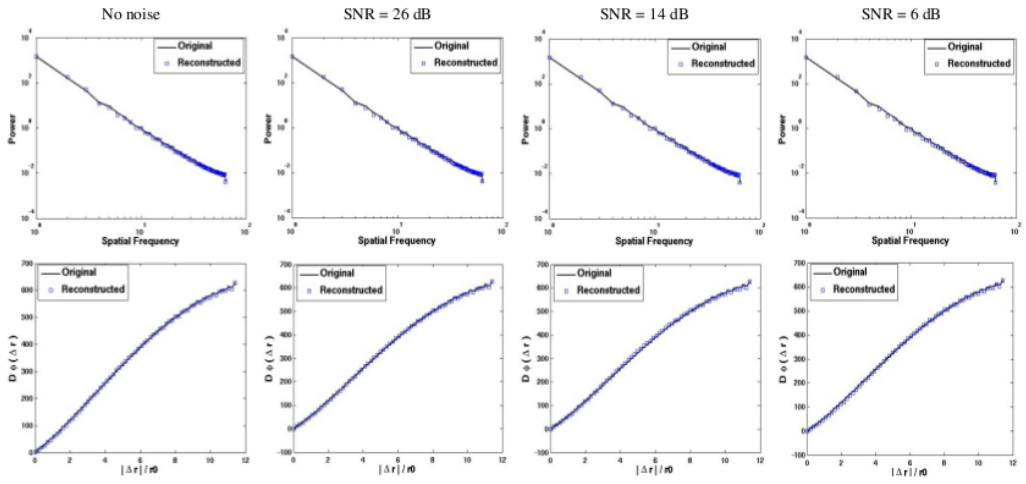


Figure 9. Results showing the robustness of the multiscale phase reconstruction algorithm for Adaptive Optics (AO) under various conditions of noise.

gradient measurements using the MMF. We also validate the results using standard validation techniques in Adaptive Optics (log power spectrum, structure functions). See figure 9 .

- Related publications: [18], [19].

6.6. Discriminative learning for Automatic speaker recognition

Participants: Reda Jourani [correspondant], Khalid Daoudi, Régine André-Obrecht, Driss Aboutajdine.

We continued our work aiming at developing efficient versions of Large Margin Gaussian Mixture Models (LM-GMM) for speaker identification. We developed a new and efficient learning algorithm and evaluated it on NIST-SRE'2006 data. The results show that, combined with the channel compesentation technique SFA, this new algorithm outperforms the state-of-the-art discriminative method GMM-supervectors SVM combined with NAP compensatation.

- Related publication: [10].

6.7. Speech Analysis

Participants: Vahid Khanagha [correspondant], Khalid Daoudi, Hussein Yahia, Oriol Pont.

- Development of a GCI detection algorithm (Vahid Khanagha, Khalid Daoudi, Hussein Yahia). According to the aerodynamic theory of voicing, the excitation source for voiced speech sounds is represented as glottal pulses, which to a first approximation, can be considered to occur at discrete instants of time. This major excitation usually coincides with the Glottal Closure Instants (the GCIs). The precise detection of GCIs has found many applications in speech technology: accurate estimation of vocal tract system, pitch marking of speech for pitch synchronous speech processing algorithms, conversion of pitch and duration of speech recordings, prosody modification and synthesis. We use the MMF for detection of these physically important instants. To do so, we study the correspondence of the Most Singular Manifold with the physical production mechanism of the speech signal and we show that this subset can be used for GCI detection. We show that, in clean speech, our algorithm has similar performance to recent methods and, in noisy speech, it significantly outperforms state-of-the-art methods. Indeed, as our algorithm is based on both time domain and inter-scale smoothings, it provides higher robustness against many types of noises. In the mean-time, the high geometrical resolution of singularity exponents prevents the accuracy to be compromised. Moreover, the algorithm extracts GCIs directly from the speech signal and does not rely on any model of the speech signal (such as the autoregressive model in linear predictive analysis). See figure 10 .
- Development of an efficient algorithm for sparse Linear Prediction Analysis (Vahid Khanagha, Khalid Daoudi). We address the problem of sparse Linear Prediction (LP) analysis, which involves the estimation of vocal tract model such that the corresponding LP residuals are as sparse as possible: for voiced sounds, one desires the residual to be zero all the time, except for few impulses at GCIs. Sparse Linear Prediction Analysis (LPA) problem has recently got much scientific attention and its classical solutions suffer from computational and algorithmic complexties. We introduce a simple closed-form solution in this chapter which is based on the minimization of weighted l_2-norm of residuals. The weighting function plays the most important role in our solution in maintaining the sparsity of the resulting residuals. We use our MSM-based GCI detector to extract from the speech signal itself, the points having the potential of attaining largest norms of residuals and then we construct the weighting function such that the prediction error is relaxed on these points. Consequently, the weighted l_2-norm objective function can be efficiently minimized by the solution of normal equations of liner least squares problem. The choice of our MSM-based GCI detector is particularly justified, considering the fact that most of the successful GCI detection methods actually use LP residuals for their detection and hence, they cannot be used for constraining the LP problem. Our algorithm is completely independent of any model that might be assumed for speech signal. We will see that when compared to classical techniques, our simple algorithm provides better sparseness

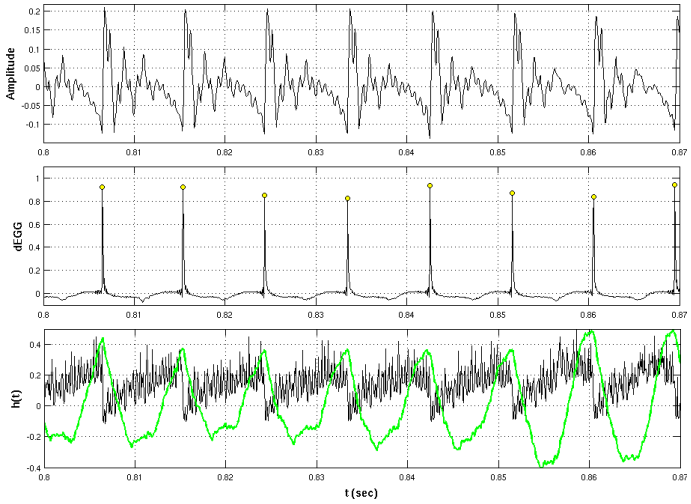


Figure 10. Top: a voiced segment of the speech signal taken from KED database. Middle: the differenced Electro-Glotto-Graph signal which serves for extraction of reference GCI points. The peaks are marked with yellow circles as the reference GCIs. Bottom: singularity exponents are shown by black color and an auxiliary functional showing changes in DC level of exponents is shown in green. The local minima of singularity exponents within each positive half-period of the auxiliary functional are taken as GCIs.

properties and does not suffer from usual instabilities. We also present an experiment to show how such sparse solution may result in more realistic estimates of the vocal tract by decoupling of the contributions of the excitation source from that of the vocal tract filter. See figure 11 .

- Multi-pulse estimation of speech excitation source (Vahid Khanagha, Khalid Daoudi). In the GCI detector algorithm, the cardinality of MSM was restricted to one sample per pitch period. We then proceed to study the significance of MSMs of higher cardinalities, in the framework of multi-pulse estimation of voiced sound excitation source. Multi-pulse source coding has been widely used and studied within the framework of Linear Predictive Coding (LPC). It consists in finding a sparse representation of the excitation source (or residual) which yields a source-filter reconstruction with high perceptual quality. The MultiPulse Excitation (MPE) method is the first and one of the most popular techniques to achieve this goal. MPE provides a sparse excitation sequence through an iterative Analysis-by-Synthesis procedure to find the position and amplitudes of the excitation source in two stages: first the location of pulses are estimated one at a time by minimization of perceptually wieghted reconstruction error. In the second stage, the amplitude of these pulses are jointly re-optimized to find the optimal pulse values. Using the MSM, we propose a novel approach to find the locations of the multi-pulse sequence that approximates the speech source excitation. We consider locations of MSM points as the locations of excitation impulses and then, the amplitude of these impulses are computed using the second stage of the classical MPE coder by minimization of the spectrally weighted mean squared error of reconstruction. The multi pulse sequence is then fed to the classical LPC synthesizer to reconstruct speech. Our algorithm is more efficient than classical methods, while providing the same level of perceptual quality as the classical MPE method. See figure 12 .
- Speech representation based local singularity analysis (Vahid Khanagha, Khalid Daoudi, Hussein Yahia, Oriol Pont). Precise estimation of singularity exponents unlocks the determination a collection of points inside the complex signal which are considered as the least predictable points (the MSM). This leads to the associated compact representation and reconstruction. This work presents the very first steps in establishing the links between the MSM and the speech signal. To do so, we make slight modifications to the formalism so as to adapt it to the particularities of the speech signal. Indeed,

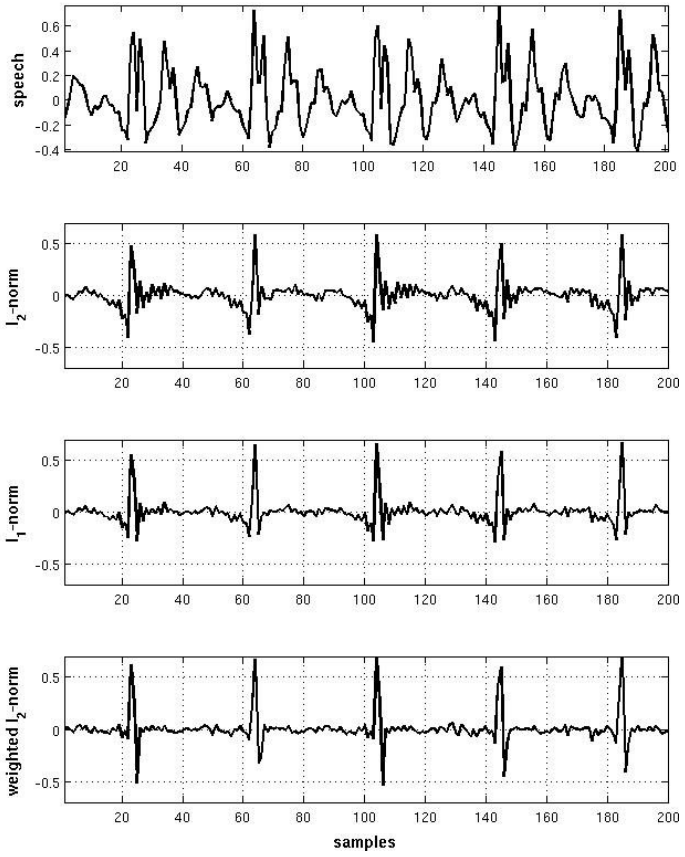


Figure 11. The residuals of the LP analysis obtained from different optimization strategies.

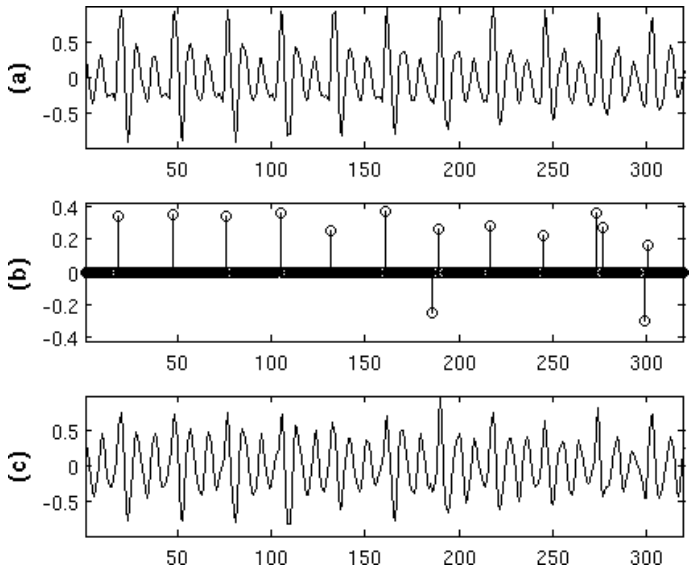


Figure 12. *(a) a 40 ms segment of stationary voiced speech, (b) the MSM excitation sequence using 7 pulses per 20 ms and (c) the corresponding reconstructed signal.*

the complex intertwining of different dynamics in speech (added to purely turbulent descriptions) suggests the definition of appropriate multi-scale functionals that might influence the evaluation of SEs, hence resulting in a more parsimonious MSM. We present a study that comforts these observations: we show that an alternative multi-scale functional does lead to a more parsimonious MSM from which the whole speech signal can be reconstructed with good perceptual quality. As MSM is composed of a collection of irregularly spaced samples, we use a classical method for the interpolation of irregularly spaced samples, called the Sauer-Allebach algorithm, to reconstruct the speech signal from its MSM. We show that by using this generic algorithm [and even by slight violation of its conditions] high quality speech reconstruction can still be achieved from a MSM of low cardinality. This shows that the MSM formed using the new multi-scale functional we define, indeed can give access to a subset of potentially interesting points in the domain of speech signal. Finally, in order to show the potential of this parsimonious representation in practical speech processing applications, we quantize and encode the MSM so as to develop a waveform coder. See figure 13 .

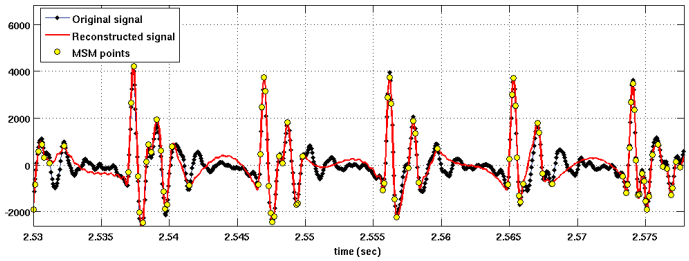


Figure 13. *Waveforms of the original signal and the reconstructed signal. Samples belonging to MSM are marked with yellow circles.*

- Related publications: [10], [17], [11].

6.8. Reconstruction and gradient-based video editing

Participants: Hicham Badri [correspondant], Hussein Yahia, Driss Aboutajdine.

Figure 14. From left to right: original image and examples of non-photoralistic rendering.

Figure 15. Top left: original image. Top right: object removal with FFT-reconstruction algorithm. Botton left: object removal with MVC (Mean Value Coordinates) algorithm. Bottom right: object removal by numerical solving of Poisson equation.

Gradient-domain methods have become a standard for many computational photography applications including object cloning, panorama stitching and non-photorealistic rendering. Integration from a vector field is required to perform gradient-domain-based applications and this operation must be fast enough for interactive editing. The most popular way to perform this integration is known as the Poisson equation and requires solving a large linear system that becomes more costly as the region of interest becomes larger. We propose to use an FFT-based solution and the framework of reconstructible systems instead of performing interactive local/global editing in the gradient domain on the CPU/GPU for both images and videos. See figures 14 , 15 .

- Related publication: [21].

MC2 Project-Team

6. New Results

6.1. Multi-fluid flows

- Microfluidics : Participants: Charles-Henri Bruneau, Johana Pinilla (PhD), Sandra Tancogne (MCF Reims).
  To handle oil recovery by chemical processes it is useful to better understand the behaviour of multifluids flows in a saturated soil. The porous medium is mimiced by a network of micro channels. The simulation of immiscible multi-fluids flows is then performed by means of the level-sets and the penalization methods to track the interfaces between the fluids and to get rid of the geometry difficulties. In addition the Cox law is added in the model to better move the interfaces during the simulations.
  Concerning visco-elastic fluids in micro-channel, one has often to compute solutions of system for which the viscosity in the stokes part is much smaller than that involved in the extra-stress. In his thesis, V. Huber has constructed a second order scheme solving Stokes equations for a bifluid flow with surface tension on a cartesian grid using a mixte finite volume-finite element approach.

6.2. Cancer modelling

We have improved our generic mathematical models describing tumor growth. These models were then specialized for several types of cancer (thyroidal lung nodules, brain tumors). The algorithm used to recover the parameters of these models from medical images has also been greatly improved and is now adapted to run on HPC architectures.

- Secondary tumors in the lung:
  The mathematical models describing the growth of secondary in the lungs have now settled and are well understood. The main focus of the year was to keep on using these models on patient data. New clinical case were selected by clinicians from the Institut Bergonié, there are currently under study. The model is currently able to reproduce the growth observed on 5 clinical cases. In 2011, various improvements to the calibration algorithms were made. The initial seeding of the algorithms was a weak point of the procedure. This has been much improved using a genetic algorithm. A complete rewrite of the routines was done to improve their versatility and efficiency. Previously, the numerical simulations and calibration were performed in 2D (clinicians selected the most relevant slice showing the evolution of the tumor). Work is now ongoing to switch to full 3D computations and calibration.
- Metastasis to the liver of a GIST
  Gastro-Intestinal Stromal Tumors often create metastasis to the liver. We have modeled the response to the treatment of such lesion starting from CT-scans.
- Modeling glioblastomas:
  In 2011, a hierarchy of models describing the growth of brain tumors was developed (and described in a submitted paper) in collaboration with University of Alabama at Birmingham. As we wished to obtain models that could be calibrated from patient data and yet be reasonably accurate, we believe that these models are suitable trade-offs between the simplicity of the SwansonÕs model (the only one used on patient data of brain tumors so far) and the accuracy of more complex models (that cannot really produce quantitative results). In particular, two models were built. The first one allows to study the efficacy of anti-angiogenic therapies. It seems to predict that the efficacy of these treatments is limited, this could be confirmed by a world-wide ongoing clinical study. The second model has been validated and we are trying to recover its parameters for a patient in 3D (which is a rather unique initiative to our knowledge).
- Modelling of electrochemotherapy :

Two articles related to the electrical cell modelling have been done ([64], [61]) . The first one deals with the influence of the ionic fluxes on the transmembrane voltage potential and on the cell volume. The main insight of the results consists in linking the transmembrane potential with the cell volume: it has been observed experimentally that cells with a low voltage potential do divide, whereas cells with high voltage potential do not, and the obtained relationship between voltage potential and cell volume can provide an explanation. The second article deals with a new model of cell electroporation essentially based on the experimental results of the I.G.R. In this paper we describe precisely the model, which takes into account the main experimental results in the electroporation process, and we present a variationnal formulation inherent to the model that leads to new efficient schemes in order to numerically solve the involved P.D.E.
The article describing a new electrical model of classical has been accepted in Journal of Math Biology [27]. This new phenomenological model involves much less parameters than the usual models, but it still provides the qualitatively good description of the electroporation. The main feature of this model lies in the fact that it provides an intrinsic behavior of the cell membrane, which seems in accordance with the preliminary experimental results of the IGR partner. We also adapted the finite difference method developed by L. Weynans and M. Cisternino for elliptic interface problems to the electropermeabilization model developed recently by C. Poignard with O. Kavian. The new method has been validated by convergence tests and comparison with other models. We have proven that in one dimension the numerical solution converges to the solution of the exact problem.

- Cell Migration modelling:
  The collaboration with IECB (University of Bordeaux) has continued with the postdocatoral position of Julie Joie. We have obtain a continuous model of cell density evolving on micropatterned polymers. The research report RR 7998 will be published in Math. Biosci. and Eng. A discrete model describing the single cells motility is being written.

  We also have started a collaboration with the University of Osaka (Japan), thanks to a PHC Sakura project, on the invadopodia. C. Poignard has been invited at Osaka in februray by Prof. Suzuki and T.Colin and C.Poignard have been at Osaka in september. A model describing the destruction of the extracellular matrix by the MMP enzyme, and then the cell migration has been obtained. R. Mahumet, a PhD student of Prof. Suzuki is developing a code to simulate the model.

6.3. Newtonian fluid flows simulations and their analysis

- Simulations of water distribution systems :Water losses may constitute a large amount of the distributed total water volume throughout water distribution systems. Here, a new model method is proposed that intends to minimize the total water volume distributed through leakage reduction. Our group has worked on the derivation of advection-reaction-diffusion type equations with an explicit relationship between the local pressure and the leakage rate. An original splitting technique to solve this type of hydraulic problem was then achieved. This technique allows pressure-dependent leakage to be taken into account, whereas in most models leakage is assumed to be uniform along a pipe. Finally, a constrained optimization problem was formulated for leakage reduction in WDS. The control variable had the mean of a local head loss and is considered in the Boundary Conditions to avoid dealing with discontinuities in the governing equations. The objective function to minimize was a regularization of the total water volume distributed. Specific operational constraints were added to ensure enough pressure at consumption points. The direct solution for this minimization problem was sought with a Gradient type method. The leakage reduction was proven to be significant in a case study. The percentage of leakage reduced from 24% to 10% in the linear relationship between pressure and leakage flow rate. With other leakage exponents, the same rate of reduction was achieved . The method was applied on a real network in the South-West of France. Controlling the pressure at two different strategic points permits a significant amount of the total distributed water to be saved (5%). This work was performed in collaboration with Cemagref Bordeaux . Future work will consist of applying a sensibility analysis of control location points to optimize the method.

- Incompressible flows : modeling and simulation of moving and deformable bodies. The incompressible Navier-Stokes equations are discretized in space onto a fixed cartesian mesh. The deformable bodies are taken into using a first order penalization method and/or second order immersed boundary method. The interface between the solid and the fluid is tracked using a level-set description so that it is possible to simulate several bodies freely evolving in the fluid. A turbulence model based on Samgorinsky model has been added to the numerical code. The numerical code written in the C langage is massively parallel. The large linear systems (over than 100 millions of dofs) are solved using the Petsc Library. As an illustration of the methods, fish-like locomotion is analyzed in terms of propulsion efficiency. Underwater maneuvering and school swimming are also explored. We were able to simulate the three-dimensional flow about a swimmer for realistic physical configurations. Another application is the turbulent 3D flow around complex wind turbine (see http://www.math.u-bordeaux1.fr/~mbergman and http://www.math.u-bordeaux1.fr/MAB/mc2/analysis.html for simulation movies). Wake flows generated by boat propellers are also modeled and simulated.
  We recently take in account a simplified elasticity model of the swimmer (elastic caudal tail of a fish). Some elastic parameters allows to increase the swimming efficiency around 20%-30%. Recent developments on multiphase flows have been performed. We are able to simulate water/air interactions with interface regularization. The interface with a boat is also taken into account. See http://www.math.u-bordeaux1.fr/~mbergman for simulations.
- Turbulence flow on an hemisphere : Participants: Charles-Henri Bruneau, Patrick Fischer (MCF Bordeaux 1), Yong Liang Xiong (PostDoc)
  ANR Cyclobulle lead by Hamid Kellay Soap hemi-bubble film experiments have shown some links between the formation of vortices when the hemi-bubble is heated at the equator and the formation of tornados in the earth atmosphere. Two-dimensional simulations using a stereographic map are used to compare to these experimental results and confirm the results when Coriolis force and heat source terms are added.
- Compressible flows: Immersed boundary methods. We are concerned with immersed boundary methods, i.e., integration schemes where the grid does not fit the geometry, and among this class of methods, more specifically with cartesian grid methods, where the forcing accounting for the presence of boundaries is performed at the discrete level. We have developed a simple globally second order scheme inspired by ghost cell approaches to solve compressible flows, inviscid as well as viscous. In the fluid domain, away from the boundary, we use a classical finite-volume method based on an approximate Riemann solver for the convective fluxes and a centered scheme for the diffusive term. At the cells located on the boundary, we solve an ad hoc Riemann problem taking into account the relevant boundary condition for the convective fluxes by an appropriate definition of the contact discontinuity speed. This method can easily be implemented in existing codes and is suitable for massive parallelization. It has been validated in two dimensions for Euler and Navier-Stokes equations, and in three dimensions for Euler equations. The order of convergence is two in L^2 norm for all variables, and between one and two in L^∞ depending on the variables. The 3D code has been parallelized with MPI. The case of a moving solid has been tested (flapping wing) and gives results for the drag and the lift in agreement with the references in the literature.
  The Oldroyd B constitutive model is used to study the role of the viscoelasticity of dilute polymer solutions in two-dimensional flows past a bluff body using numerical simulations. This investigation is motivated by the numerous experimental results obtained in quasi two dimensional systems such as soap film channels. The numerical modeling is novel for this case and therefore a comprehensive comparison is carried out to validate the present penalization method and artificial boundary conditions. In particular we focus on flow past a circular object for various values of the Reynolds number, Weissenberg number, and polymer viscosity ratio. Drag enhancement and drag reduction regimes are discussed in detail along with their flow features such as the pattern of vortex shedding, the variation of lift as well as changes in pressure, elongational rates, and polymer stress profiles. A comprehensive study of the flow behavior and energy balance are carefully carried out for high

Reynolds numbers. Flow instabilities in both numerical and experimental results are discussed for high Weissenberg numbers .

- Elliptic problems: We have developed a new cartesian method to solve elliptic problems with immersed interfaces. These problems appear in numerous applications, among them: heat transfer, electrostatics, fluid dynamics, but also tumour growth modelling, or modelling of electric potential in biological cells This method is second order accurate in the whole domain, notably near the interface. The originality of the method lies on the use of additionnal unknows located on interface points, on which are expressed flux equalities. Special care is dedicated to the discretization near the interface, in order to recover a stable second order accuracy. Actually, a naive discretization could lead to a first order scheme, notably if enough accuracy in the discretization of flux transmission condtions is not provided. Interfaces are represented with a distance level-set function discretized on the grid points. The method has been validated on several test-cases with complex interfaces in 2D. A parallel version has been developed using the PETSC library.
- Simulations of fluid-solid interactions : The interaction of an elastic structure and an fluid occurs in many phenomena in physics. To avoid the difficulty of coupling lagrangian elasticity with an eulerian fluid we consider a whole eulerian formulation. The elasticity of the structure is computed with retrograde caracteristics which satisfy a vectorial transport equation. We derive the associated fluid-structure models for incompressible and compressible media. The equations are discretized on a cartesian mesh with finite differences and finite volumes schemes. The applications concern the bio-locomotions and the study of air-elastic interaction.
- Vortex methods : The aim of this work is to couple vortex methods with the penalization methods in order to take advantage from both of them. This immersed boundary approach maintains the efficiency of vortex methods for high Reynolds numbers focusing the computational task on the rotational zones and avoids their lack on the no-slip boundary conditions replacing the vortex sheet method by the penalization of obstacles. This method that is very appropriate for bluff-body flows is validated for the flow around a circular cylinder on a wide range of Reynolds numbers. Its validation is now extended to moving obstacles (axial turbine blades) and three-dimensional bluff-bodies (flow around a sphere). See [77]. Moreover, using the global properties of the penalization method, this technique permits to include porous media simultaneously in the flow computation. We aim to adapt the porous media flows to our new method and to apply it in order to implement passive control techniques using porous layers around bluff-bodies.
- Domain decomposition : Domain decomposition methods are a way to parallelize the computation of numerical solutions to PDE. To be efficient, domain decompositions methods should converge independently on the number of subdomains. The classical convergence result for the additive Schwarz preconditioner with coarse grid is based on a stable decomposition. The result holds for discrete versions of the Schwarz preconditioner, and states that the preconditioned operator has a uniformly bounded condition number that depends only on the number of colors of the domain decomposition, and the ratio between the average diameter of the subdomains and the overlap width. Constants are usually non explicit and are only asserted to depend on the "shape regularity" of the domain decomposition.
  two years ago, we showed the result holds the additive Schwarz preconditioner can also be defined at the continuous level and provided completely explicits estimates. Last year, we established that a similar result also holds for non shape regular domain decompositions where the diameter of the smallest subdomain is significantly smaller than the diameter of the largest subdomain. The constants are also given explicitely and are independent of the ratio between the diameter of the largest sudomain and the diameter of the smallest subdomain.
  This year, we have studied explored new coarse spaces algorithms for domain decomposition methods. Coarse spaces are necessary to get a scalable algorithm whose convergence speed does not deteriorate when the number of subdomains increases. For domains decomposition methods with discontinuous iterates, we showed that continuous coarse spaces can never be an optimal choice. As

an alternative, we introduced both the use of discontinuous coarse spaces(DCS) and a new coarse space algorithm using these discontinuous coarse spaces.

6.4. Flow control and shape optimization

- Flow control : Participants: Charles-Henri Bruneau, Iraj Mortazavi, Emmanuel Creusé (Lille), Patrick Gilliéron (Paris).

  An efficient active control of the two- and three-dimensions flow around the 25 degrees rear window Ahmed body has been performed. A careful theoretical and numerical study of the trajectories of the vortices allows to adapt the control in order to improve its efficiency and get a better drag reduction.

6.5. Calculation of Ice Chunk Trajectory

- Participants: Héloise Beaugendre, Ramesh Yapalparvi.
  In this work, calculation of trajectories of ice chunk are carried out at varying values of ratio of density of ice piece to that of the ambient fluid. Proper Orthogonal Decomposition with Interpolation (PODI) method is then applied on snapshots of trajectories simulated by computational fluid dynamics. Snapshots of trajectories are obtained based on cartesian grids, penalization, and level sets. The extracted POD modes from snapshots are then used to reconstruct solutions and capabilities of POD with interpolation are demonstrated on ice trajectory calculations for flow around iced airfoil and cylinder for density ratio's that are not part of the snapshot set.

REALOPT Project-Team

6. New Results

6.1. Theoretical and Methodological Developments

Participants: Andrew Miller, Arnaud Pêcher, Pierre Pesneau, Ruslan Sadykov, Gautier Stauffer, François Vanderbeck.

We made progress in the development of theory and algorithms in the area of "Reformulation and Decomposition Approaches for MIP", "Mixed Integer Nonlinear Programming", and "Polyhedral Combinatorics and Graph Theory".

6.1.1. Column Generation for Extended Formulations

Working in an extended variable space allows one to develop tight reformulations for mixed integer programs. However, the size of the extended formulation grows rapidly too large for a direct treatment by a MIP-solver. Then, one can work with inner approximations defined and improved by generating dynamically variables and constraints. The alternative considered in [21] is an inner approximation obtained by generating dynamically the variables of the extended formulation. It assumes that the extended formulation stems from a decomposition principle. Then one can implement column generation for the extended formulation using Dantzig-Wolfe decomposition paradigm. Pricing subproblem solutions are expressed in the variables of the extended formulation and added to the current restricted version of the extended formulation along with the subproblem constraints that are active for the subproblem solutions.

Our paper [21] revisits the column-and-row generation approach, which is viewed herein as a generalization of standard column generation, the latter being based on a specific subproblem extended formulation. This generic view not only highlights the scope of applicability of the method, but it also leads to a more general termination condition than the traditional reduced cost criteria and to theoretically stronger dual bounds. We highlight a key benefit of the latter: lifting pricing problem solutions in the space of the extended formulation permits their recombination into new subproblem solutions and results in faster convergence.

The interest of the approach is evaluated numerically on machine scheduling, bin packing, generalized assignment, and multi-echelon lot-sizing problems. We compare a direct handling of the extended formulation, a standard column generation approach, and the "column-and-row generation" procedure. The results illustrate the stabilization effect resulting from column disaggregation and recombinations that is shown to have a cumulative effect when used in combination with a standard stabilization technique.

6.1.2. Primal Heuristics for Branch-and-Price

Primal heuristics have become an essential component in mixed integer programming (MIP). Generic heuristic paradigms of the literature remain to be extended to the context of a column generation solution approach. Our goal is to derive black-box primal heuristics for use in Branch-and-Price approaches. This requires extending primal heuristic paradigms to the context of dynamic generation of the variables of the model. We highlight an important fact: such generic tools typically performs better than problem specific meta-heuristics, in terms of solution quality and computing times. Based on our application specific experience with these techniques [55], [57], [72], [73], and on a review of generic classes of column generation based primal heuristics, in [49], we are developing a full blown review of such techniques, completed with new methods and an extensive numerical study. This research is being carried on in collaboration with the members of the associated team project, SAMBA [27] [30].

As a Dantzig-Wolfe reformulation is typically tighter than the original compact formulation, techniques based on rounding its linear programming solution have better chance to yield good primal solutions. The aggregated information built into the column definition and the price coordination mechanism provide a global view at the solution space that may be lacking in somewhat more "myopic" approaches based on compact formulations. However, the dynamic generation of variables requires specific adaptation of heuristic paradigms. Our contribution [30] lies in proposing simple strategies to get around these technical issues. We initially concentrate on "diving" methods and consider their combination with "sub-MIPing", relaxation induced neighborhood search, truncated backtracking using a Limited Discrepancy Search. These add-ons serves as local-search or diversification/intensification mechanisms. The methods are numerically tested on standard models such as Cutting Stock, Vertex Coloring, Generalized Assignment, Lot-Sizing, and Vehicle Routing problems. We further extend this research by combining the "diving" method mentioned above with the "feasibility pump" approach [27]. We show how this combination can be implemented in a context of dynamically defined variables, and we report on numerically testing "feasibility pump" for cutting stock and generalized assignment problems.

6.1.3. Stabilization techniques for column generation

Within the SAMBA project, we are collaboratively studying techniques to accelerate the convergence of column generation algorithms [25]. This techniques exploit Lagrangian duality theory. By revisiting all the alternative approaches to solving the Lagrangian dual, we identify suitable combinations of paradigms.

We also bridge the gap with techniques used in the dual framework of cut generation that have their unexploited counterpart for column generation [32], [29]. Cutting plane algorithmic strategies translate into stabilization procedures for column generation. We establish the link between the in-out separation procedure and dual price smoothing techniques for column generation. In this framework, we develop generic convergence proofs and effective smoothing auto-regulating strategies that avoids the need for parameter tuning. We further improve performance of such stabilization by hybridization with an ascent method. This work might inspire novel cut separation strategies.

6.1.4. Stable sets in claw-free graphs

A *stable set* is a set of pairwise non adjacent vertices in a graph and a graph is *claw-free* when no vertex contains a stable set of size three in its neighborhood. Given weights on the vertices, the stable set problem (a NP-hard problem in general) consists in selecting a set of pairwise non adjacent vertices maximizing the sum of the selected weights. The stable set problem in claw-free graphs is a fundamental generalization of the classic matching problem that was shown to be polynomial by Minty in 1980 (G. Minty. *On maximal independent sets of vertices in claw-free graphs*. J. Combinatorial Theory B, 28:284-304 (1980)). However, in contrast with matching, the polyhedral structure (i.e. the integer hull of all stable sets in a claw-free graph) is not very well understood and thus providing a 'decent' linear description of this polytope has thus been a major open problem in our field.

We proposed a new algorithm to find a maximum weighted stable set in a claw-free graph [38] whose complexity is now drastically better than the original algorithm by Minty (n^3 versus n^6, where n is the number of vertices). We also provided a description of the polyhedra in an extended space (i.e. using additional artificial variables) and an *efficient procedure* to separate over the polytope in polynomial-time [26]. Beside those main contributions, we published another papers on the strongly minimal facets of the polytope.

6.1.5. The Circular-Chromatic number

Another central contribution of our team concerns the chromatic number of a graph (the minimum number of independent stable sets needed to cover the graph). We proved that the chromatic number and the clique number of some superclasses of perfect graphs is computable in polynomial time [17].

We investigated the circular-chromatic number. It is a well-studied refinement of the chromatic number of a graph (designed for problems with periodic solutions): the chromatic number of a graph is the integer ceiling of its circular-chromatic number. Xuding Zhu noticed in 2000 that circular cliques are the relevant circular

counterpart of cliques, with respect to the circular chromatic number, thereby introducing circular-perfect graphs, a super-class of perfect graphs.

We proved that the clique and chromatic numbers of circular-perfect graphs is computable in polynomial time [16], thereby extending Grötschel, Lovász and Schrijver's result to the whole family of circular-perfect graphs. We gave closed formulas for the Lovász Theta number of circular-cliques (previously, closed formulas were known for circular-cliques with clique number at most 3 only), and derived from them that the circular-chromatic number of circular-perfect graphs is computable in polynomial time [24].

6.2. Model Specific Developments and Applications

Participants: Andrew Miller, Arnaud Pêcher, Pierre Pesneau, Ruslan Sadykov, Gautier Stauffer, François Vanderbeck.

The models on which we made progress can be partitioned in three areas: "Packing and Covering Problems", "Network Design and Routing", and "Planning, Scheduling, and Logistic Problems".

6.2.1. Bin-Packing with Conflicts

The bin-packing problem consists in finding the minimum number of bin of fixed size one needs to pack a set of items of different sizes. We studied a generalization of this problem where items can be in conflicts and thus cannot be put together in the same bin. We show in [20] that the instances of the literature with 120 to 1000 items can be solved to optimality with a generic Branch-and-Price algorithm, such as our prototype BaPCod, within competitive computing time. Moreover, we solved to optimality all the 37 open instances. The approach involves generic primal heuristics, generic branching, but a specific pricing procedure.

6.2.2. Using graph theory for solving orthogonal knapsack problems

We investigated the orthogonal knapsack problem, with the help of graph theory. The multi-dimensional orthogonal packing problem (OPP) is defined as follows: given a set of items with rectangular shapes, the problem is to decide whether there is a non-overlapping packing of these items in a rectangular bin. The rotation of items is not allowed. A powerful characterization of packing configurations by means of interval graphs was introduced by Fekete and Schepers using an efficient representation of all geometrically symmetric solutions by a so called *packing class* involving one *interval graph* (whose complement admits a transitive orientation: each such orientation of the edges corresponds to a specific placement of the forms) for each dimension. Though Fekete & Schepers' framework is very efficient, we have however identified several weaknesses in their algorithms: the most obvious one is that they do not take advantage of the different possibilities to represent interval graphs.

In [12], [11], we give two new algorithms: the first one is based upon matrices with consecutive ones on each row as data structures and the second one uses so-called MPQ-trees, which were introduced by Korte and Mohring to recognize interval graphs. These two new algorithms are very efficient, as they outperform Fekete and Schepers' on most standard benchmarks.

6.2.3. Inventory routing and logistics problems

Inventory routing problems combine the optimization of product deliveries (or pickups) with inventory control at customer sites. in [13], we considered the planning of single product pickups over time: each site accumulates stock at a deterministic rate; the stock is emptied on each visit. Our objective is to minimize a surrogate measure of routing cost while achieving some form of regional clustering by partitioning the sites between the vehicles. The fleet size is given but can potentially be reduced. Planning consists in assigning customers to vehicles in each time period, but the routing, i.e., the actual sequence in which vehicles visit customers, is considered as an "operational" decision. We developed a truncated branch-and-price algorithm. This exact optimization approach is combined with rounding and local search heuristics to yield both primal solutions and dual bounds that allow us to estimate the deviation from optimality of our solution. We were confronted with the issue of symmetry in time that naturally arises in building a cyclic schedule (cyclic permutations along the time axis define alternative solutions). Central to our approach is

a state-space relaxation idea that allows us to avoid this drawback: the symmetry in time is eliminated by modeling an average behavior. Our algorithm provides solutions with reasonable deviation from optimality for large scale problems (260 customer sites, 60 time periods, 10 vehicles) coming from industry. The subproblem is interesting in its own right: it is a multiple-class integer knapsack problem with setups. Items are partitioned into classes whose use implies a setup cost and associated capacity consumption.

6.2.4. Scheduling

Cross docking terminals allow companies to reduce storage and transportation costs in a supply chain. At these terminals, products of different types from incoming trucks are unloaded, sorted, and loaded to outgoing trucks for delivery. In [19], we focus on the operational activities at a cross docking terminal with two doors: one for incoming trucks and another one for outgoing trucks. We consider the truck scheduling problem with the objective to minimize the storage usage during the product transfer inside the terminal. Our interest in this problem is mainly theoretical. We show that it is NP-hard in the strong sense even if there are only two product types. For a special case with fixed subsequences of incoming and outgoing trucks, we propose a dynamic programming algorithm, which is the first polynomial algorithm for this case. The results of numerical tests of the algorithm on randomly generated instances are also presented.

In [18], we consider the scheduling jobs in parallel, i.e., jobs can be executed on more than one processor at the same time. With the emergence of new production, communication and parallel computing system, the usual scheduling requirement that a job is executed only on one processor has become, in many cases, obsolete and unfounded. In this work, we consider the NP-hard problem of scheduling malleable jobs to minimize the total weighted completion time (or mean weighted flow time). For this problem, we introduce the class of "ascending" schedules in which, for each job, the number of machines assigned to it cannot decrease over time while this job is being processed. We prove that, under a natural assumption on the processing time functions of jobs, the set of ascending schedules is dominant for the problem. This result can be used to reduce the search space while looking for an optimal solution.

Currently, we are working on a scheduling application at a port. For this application, an equipment routing task scheduling problem [28] has been formulated, where a set of tasks needs to be performed. Tasks require equipment of different types. A particularity of the problem is that an equipment needs to be moved to the actual locations of tasks which use this equipment. So, there are both scheduling and routing decisions are to be taken simultaneously.

6.2.5. One warehouse multi-retailer problem

The *One-Warehouse Multi-retailer problem (OWMR)* is a very important NP-hard inventory control problem arising in the distribution of goods when one central warehouse is supplying a set of final retailers facing demand from customers. In [22], we provide a simple and fast 2-approximation algorithm for this problem (i.e. an algorithm ensuring a deviation by a factor at most two from the optimal solution). This result is both important in practice and in theory as it allows to approximate large real-world instances of the problem (we implemented this algorithm at IBM and it is within 10% of optimality in practice) and the techniques we developed appear to apply to more general settings. We are extending our results to other inventory control problems.

6.3. Software prototypes, Generic Developments and Specific Tools

Participants: Romain LeGuay, Pierre Pesneau, Ruslan Sadykov, François Vanderbeck.

6.3.1. BaPCod - a generic branch-and-price code

The development of the prototype software platform is supported by our junior engineer, Romain Leguay. He developed a new interface with the underlying MIP solver allowing multiple solvers to be called in the same run. He then re-organized the svn depository and a web distribution platform in view of the increasing number if users to whom Romain offers precious support. Romain has then redesigned parts of the code in the perspective of its parallelization and contributed to designing a pseudo modeling language for a friendly user interface. The emphasis is currently on enhancing the code performance in particular through rapid access data structure. Romain also participates to the setting up of stabilization and preprocessing algorithms.

The software platform BaPCod is continuously improved to include all the methodological features that arise from our research, in particular in our collaborative project with Brazil: SAMBA. BaPCod serves there as a proof-of-concept code and is useful for the transfer of knowledge between the parties, including the company GAPSO (a Brazilian spin-up launched by these academics).

CARMEN Team

5. New Results

5.1. Models

- [12]: we explain the links between the solutions of the bidomain and monodomain models using some analytical arguments. The result is partially based on the theory of the bidomain operator explained in [11].
- [23]: Fibre structure and anisotropy is a determinant issue to provide accurate simulations of the electrical activity of atrial tissue. Though, atrial fibre architecture remains unreachable to standard imagery techniques on patients. A method to construct models of the fibre architecture on patient-specific geometries is then a key for numerical simulations of atrial tissues. Such a method is proposed. Pathological and non pathological patient specific surface models of the left atria (LA) are defined. Hence, a pathological scenario is explored : a mechanism of micro- reentry in the left superior pulmonary vein (LSPV) and its interaction with the sinus rhythm (SR).

5.2. Numerical techniques

- [19]: In this paper we propose a preconditioning for the bidomain model either for an isolated heart or in an extended framework including a coupling with the surrounding tissues (the torso). The preconditioning is based on a formulation of the discrete problem that is shown to be symmetric positive semi-definite. A block LU decomposition of the system together with a heuristic approximation (referred to as the monodomain approximation) are the key ingredients for the preconditioning definition. Numerical results are provided for two test cases: a 2D test case on a realistic slice of the thorax based on a segmented heart medical image geometry, a 3D test case involving a small cubic slab of tissue with orthotropic anisotropy. The analysis of the resulting computational cost (both in terms of CPU time and of iteration number) shows an almost linear complexity with the problem size, i.e. of type nlogα(n) (for some constant α) which is optimal complexity for such problems.

5.3. Medical applications of numerical models

- [26]: We computed some bidomain solutions for use by M. Pop and M. Sermesant in the STACOM'11 challenge from the MICCAI 2011 conference and derived collaborative article [26].
- [18]: The aim of this study was to describe a new familial cardiac phenotype and to elucidate the electrophysiological mechanism responsible for the disease. Mutations in several genes encoding ion channels, especially SCN5A, have emerged as the basis for a variety of inherited cardiac arrhythmias. Three unrelated families comprising 21 individuals affected by multifocal ectopic purkinje-related premature contractions (MEPPC) characterized by narrow junctional and rare sinus beats competing with numerous premature ventricular contractions with right and/or left bundle branch block patterns were identified. All the affected subjects carried the same transition in the SCN5A gene. Patch-clamp studies revealed a net gain of function of the sodium channel, leading, in silico, to incomplete repolarization in Purkinje cells responsible for premature ventricular action potentials. In vitro and in silico studies recapitulated the normalization of the ventricular action potentials in the presence of quinidine.
- [22]: In some cases, the standard methods to construct activation maps based on the derivatives of the signals may lead to inaccurate results. In this paper, we evaluated a novel Directional Activation Algorithm (DAA) based on EGM analysis. The DAA calculates the time delays between adjacent EGMs and assigns to each a localized propagation vector. The accuracy of the proposed methodology is compared with known activities obtained from a monodomain, isotrope, Beeler-Reuter model of the atria.

- [20]: Although the ECG is a widely used tool, the ionic basis underlying its changes caused by drugs and diseases are often unclear. In this work we present a computational model of the human ECG capable of representing drug-induced effects from the ionic to the surface potential level. We use the state-of-the-art bidomain model coupled to a membrane kinetics model in the heart and the Laplace equation in the torso. The membrane kinetics are represented by a detailed physiological human action potential model. We modified the potassium (respectively sodium) representation in the model in order to introduce the ion channel/drug interactions representing classIII (respectively class I) drugs. The drug model is represented by an ion channel conduction block depending on the IC50 value and the drug dose. We conduct numerical simulation of the ECGs measured on the surface of the thorax and could assess each of the potassium and sodium block effects (for class I and class III drugs).

5.4. Inverse problems

- [24]: The treatment of atrial fibrillation has greatly changed in the past decade. Ablation therapy, in particular pul- monary vein ablation, has quickly evolved. However, the sites of the trigger remain very difficult to localize. In this study we propose a machine-learning method able to non-invasively estimate a single site trigger. The machine learning technique is based on a kernel ridge regression algorithm. In this study the method is tested on a simulated data. We use the monodomain model in order to simulate the electrical activation in the atria. The ECGs are computed on the body surface by solving the Laplace equation in the torso.
- [16]: In the present paper, an optimal control problem constrained by the tridomain equations in electrocardiology is investigated. The state equations consisting in a coupled reaction–diffusion system modeling the propagation of the intracellular and extracellular electrical potentials, and ionic currents, are extended to further consider the effect of an external bathing medium. The existence and uniqueness of solution for the tridomain problem and the related control problem is assessed, and the primal and dual problems are discretized using a finite volume method which is proved to converge to the corresponding weak solution. In order to illustrate the control of the electrophysiological dynamics, we present some preliminary numerical experiments using an efficient implementation of the proposed scheme.
- [17]: This note is devoted to the analysis of the null controllability of a nonlinear reaction–diffusion system, approximating a parabolic–elliptic system, modeling electrical activity in the heart. The uniform, with respect to the degenerating parameter, null controllability of the approximating system by a single control force acting on a subdomain is shown. The proof needs a precise estimate with respect to the degenerating parameter and it is done combining Carleman estimates and energy inequalities.

MAGIQUE-3D Project-Team

6. New Results

6.1. Inverse Problems

6.1.1. Reconstruction of an elastic scatterer immersed in a homogeneous fluid

Participants: Hélène Barucq, Rabia Djellouli, Élodie Estecahandy.

The determination of the shape of an obstacle from its effects on known acoustic or electromagnetic waves is an important problem in many technologies such as sonar, radar, geophysical exploration, medical imaging and nondestructive testing. This inverse obstacle problem (IOP) is difficult to solve, especially from a numerical viewpoint, because it is ill-posed and nonlinear. Its investigation requires as a prerequisite the fundamental understanding of the theory for the associated direct scattering problem, and the mastery of the corresponding numerical solution methods.
In this work, we are interested in retrieving the shape of an elastic obstacle from the knowledge of some scattered far-field patterns, and assuming certain characteristics of the surface of the obstacle. The corresponding direct elasto-acoustic scattering problem consists in the scattering of time-harmonic acoustic waves by an elastic obstacle Ω^s embedded in a homogeneous medium Ω^f, that can be formulated as follows:

$$\begin{aligned}
\Delta p + (\omega^2/c_f^2)\, p = 0 \qquad & \text{in } \Omega^f \\
\nabla \cdot \sigma(u) + \omega^2 \rho_s\, u = 0 \qquad & \text{in } \Omega^s \\
\omega^2 \rho_f u \cdot n = \partial p/\partial n + \partial e^{i\,(\omega/c_f)\,x\cdot d}/\partial n \qquad & \text{on } \Gamma \\
\sigma(u) n = -pn - e^{i\,(\omega/c_f)\,x\cdot d} n \qquad & \text{on } \Gamma \\
\lim_{r\to+\infty} r\,(\partial p/\partial r - i\,(\omega/c_f)\,p) = 0 &
\end{aligned} \tag{2}$$

where p is the fluid pressure in Ω^f whereas u is the displacement field in Ω^s, and $\sigma(u)$ represents the stress tensor of the elastic material.
This boundary value problem has been investigated mathematically and results pertaining to the existence, uniqueness and regularity can be found in [86] and the references therein, among others. We propose a solution methodology based on a regularized Newton-type method for solving the IOP. The proposed method is an extension of the regularized Newton algorithm developed for solving the case where only Helmholtz equation is involved, that is the acoustic case by impenetrable scatterers [79]. The direct elasto-acoustic scattering problem defines an operator $F : \Gamma \to p_\infty$ which maps the boundary Γ of the scatterer Ω^s onto the far-field pattern p_∞. Hence, given one or several measured far-field patterns $\widetilde{p}_\infty(\widehat{x})$, corresponding to one or several given directions d and wavenumbers k, one can formulate IOPs as follows:

$$\text{Find a shape } \Gamma \quad \text{such that} \quad F(\Gamma)(\widehat{x}) = \widetilde{p}_\infty(\widehat{x}); \quad \widehat{x} \in S^1.$$

We propose a solution methodology based on a regularized Newton-type method to solve this inverse obstacle problem. At each Newton iteration, we solve the forward problem using a finite element solver based on discontinuous Galerkin approximations, and equipped with high-order absorbing boundary conditions. We have first characterized the Fréchet derivatives of the scattered field. They are solution to the same boundary value problem as the direct problem with other transmission conditions. This work has been presented both in FACM11 and in WAVES 2011. A paper has been submitted.

6.1.2. hp-adaptive inversion of magnetotelluric measurements

Participants: Hélène Barucq, Julen Alvarez Aramberri, David Pardo.

The magnetotelluric (MT) method is a passive electromagnetic (EM) exploration technique that allows to determine the resistivity distribution in the subsurface of the area of interest on scales varying from few meters to hundreds of kilometers. Commercial uses include hydrocarbon (oil and gas) exploration, geothermal exploration, and mining exploration, as well as hydrocarbon and groundwater monitoring. MT measurements are governed by the electromagnetic phenomena, which can be described by Maxwell's equations. We solve those equations by a goal-oriented hp-adaptivity Finite Element Method (FEM).

In order to estimate the resistivity distribution in the Earth's subsurface, we solve an Inverse Problem. We define a Misfit Function that represents the difference between the measured and computed data for a particular resistivity distribution. By minimizing this misfit function using a gradient based approach with model reduction techniques, and hence solving the inverse problem, we are able to determine the properties of the subsurface materials.

6.2. Modeling

6.2.1. Implementation of a non-reflecting boundary condition on ellipsoidal boundary

Participants: Hélène Barucq, Anne-Gaëlle Saint-Guirons, Sébastien Tordeux.

The modeling of wave propagation problems using finite element methods usually requires the truncation of the computational domain around the scatterer of interest. Absorbing boundary condition are classically considered in order to avoid spurious reflections. This year we have implemented and tested an exact condition based on a non local Dirichlet to Neumann operator in the context of the Helmholtz equation posed on an elongated domain.

6.2.2. Explicit computation of the electrostatic energy for an elliptical charged disc

Participants: Sophie Laurens, Sébastien Tordeux.

In [32], We have described a method to obtain an explicit expression for the electro- static energy of a charged elliptical infinitely thin disc. The charge distribution is assumed to be polynomial. Such explicit values for this energy are fundamen- tal for assessing the accuracy of boundary element method codes. The main tools used are an extension of Copson's method and a diagonalization, given by Leppington and Levine, of the single-layer potential operator associated with the electrostatic potential created by a distribution of charges on an elliptical disc.

6.2.3. A new modified equation approach for solving the wave equation

Participants: Cyril Agut, Hélène Barucq, Henri Calandra, Julien Diaz, Florent Ventimiglia.

The new method involving p-harmonic operator described in section 3.2 has been presented in [17]. We have proved the convergence of the scheme and its stability under a CFL condition. Numerical results in one, two and three-dimensional configurations show that this CFL condition is slightly greater than the CFL condition of the second-order Leap-Frog scheme.

In the framework of the PhD thesis of Florent Ventimiglia, we are now considering the extension of this technique to the first order formulation of the acoustic and elastodynamic equations. A numerical analysis of performance in 1D indicates that, for a given accuracy, this method requires less storage than the High-Order ADER Schemes for and similar computational costs. We are now implementing this algorithm in 3D in order to confirm this analysis and to assess its performance in an RTM framework on realistic configurations.

6.2.4. Stability Analysis of an Interior Penalty Discontinuous Galerkin Method for the Wave equation

Participants: Cyril Agut, Hélène Barucq, Julien Diaz.

The Interior Penalty Discontinuous Galerkin Method [72], [69], [83] we use in the IPDGFEM code requires the introduction of a penalty parameter. Except for regular quadrilateral or cubic meshes, the optimal value of this parameter is not explicitely known. Moreover, the condition number of the resulting stiffness matrix is an increasing function of this parameter, but the precise behaviour has not been explicited neither. We have carried out a theoretical and numerical study of the pnealization parameter and of the CFL condition for quadrilateral and cubic meshes, this results have been presented in a paper accepted in M2AN [16]

6.2.5. Higher Order Absorbing Boundary Conditions for the Wave Equation

Participants: Hélène Barucq, Juliette Chabassier, Julien Diaz.

The numerical simulation of wave propagation is generally performed by truncating the propagation medium and the team works on new ABCs, trying to improve the performance of existing conditions. Following the analysis performed in [23], we have considered the issue of constructing high-order ABCs for the Helmholtz equation. Now, to derive conditions of order greater than two is really technical. In addition, when the coefficients representing the geological properties of the medium are not regular, the method of construction of ABCs is not completely justified. That is why we turned to the construction of conditions that take into account all the characteristics of the diffraction phenomenon and not only waves that propagate like in the case of standrad ABCs. This is what we call enriched ABCs. A research report is being written, an article should be submitted in 2013. During 2012, a publication for the acoustic wave equation has been accepted in M3AS [23] and a second one has been submitted.

6.2.6. Multiperforated plates in linear acoustics

Participants: Abderrahmane Bendali, M'Barek Fares, Sophie Laurens, Estelle Piot, Sébastien Tordeux.

Acoustic engineers use approximate heuristic models to deal with multiperforated plates in liners and in combustion chambers of turbo-engines. These models were suffering from a lack of mathematical justifications and were consequently difficult to improve. Performing an asymptotic analysis (the small parameter is the radius of the perforations), we have justified these models and proposed some improvement. Our theoretical results have been compared to numerical simulations performed at CERFACS (M'Barek Fares) and to acoustical experiments realized at ONERA (Estelle Piot). Two papers have been published in 2012 [27], [30].

6.2.7. Performance Assessment of IPDG for the solution of an elasto-acoustic scattering problem

Participants: Hélène Barucq, Rabia Djellouli, Élodie Estecahandy.

We present a solution methodology for the direct elasto-acoustic scattering problem that falls in the category of Discontinuous Galerkin methods. The method distinguishes itself from the existing methods by combining high-order Discontinuous Galerkin approximations, local stabilizations for the coupled problem and the use of curved element edges on the boundaries. We present some numerical results that illustrate the salient features and highlight the performance of the proposed solution methodology on the resonance phenomenon existing in the elastic scatterer for simple geometries such as circles. Moreover, the designed method ensures a convergence order with a gain of two order of magnitude compared to polygonal boundaries, and a potential to address both mid- and high-frequency regimes. These results have been presented to ECCOMAS 2012 [44] and to two workshops [42] [43].

6.2.8. Operator Based Upscaling for Discontinuous Galerkin Methods

Participants: Hélène Barucq, Théophile Chaumont, Julien Diaz, Christian Gout, Victor Péron.

Scientists and engineers generally tackle problems that include multiscale effects and that are thus difficult to solve numerically. The main difficulty is to capture both the fine and the coarse scales to get an accurate numerical solution. Indeed, the computations are generally performed by using numerical schemes based on grids. But the stability and thus the accuracy of the numerical method depends on the size of the grid which must be refined drastically in the case of very fine scales. That implies huge computational costs and in particular the limitations of the memory capacity are often reached. It is thus necessary to use numerical methods that are able to capture the fine scale effects with computations on coarse meshes. Operator-based upscaling is one of them and we present in [22] a first attempt to adapt that technique to a Discontinuous Galerkin Method (DGM). We consider the Laplace problem as a benchmark and we compare the performance of the resulting numerical scheme with the classical one using Lagrange finite elements. The comparison involves both an accuracy analysis and a complexity calculus. This work shows that there is an interest of combining DGM with upscaling.

6.2.9. Asymptotic Modeling for Elasto-Acoustics

Participants: Julien Diaz, Victor Péron.

We present in [65] equivalent conditions and asymptotic models for the diffraction problem of elasto-acoustic waves in a solid medium surrounded by a thin layer of fluid medium. This problem is well suited for the notion of equivalent conditions : since the thickness of the layer is small with respect to the wavelength, the effect of the fluid medium on the solid is as a first approximation local. We derive and validate equivalent conditions up to the third order for the elastic displacement. These conditions approximate the acoustic waves which propagate in the fluid region. This approach leads us to solve only elastic equations. The construction of equivalent conditions is based on a multiscale expansion in power series of the thickness of the layer for the solution of the transmission problem.

Questions regarding the implementation of the conditions have been addressed carefully. Indeed, the boundary conditions have been integrated without changing the structure of the code Hou10ni.

This work has been presented in four international conferences and Workshops : Aquitaine-Euskadi Workshop on Applied Mathematics; First Russian-French Conference on Mathematical Geophysics, Mathematical Modeling in Continuum Mechanics and Inverse Problems; Workshop HPC-GA; Twelfth International Conference Zaragoza-Pau on Mathematics.

A paper with numerical results for the elasto-acoustic problem with a thin layer and a variable thickness is in preparation.

6.2.10. Asymptotic modeling in electromagnetism

Participants: François Buret, Monique Dauge, Patrick Dular, Laurent Krähenbühl, Victor Péron, Ronan Perrussel, Clair Poignard, Damien Voyer.

The following results rely on a problematic developed in section 3.2 , item **Asymptotic modeling**.

In the paper [28], eddy current problems are addressed in a bidimensional setting where the conducting medium is non-magnetic and has a corner singularity. For any fixed skin depth we show that the flux density is bounded near the corner, unlike the perfect conducting case. Then as the skin depth goes to zero, the first two terms of a multiscale expansion of the magnetic potential are introduced to tackle the magneto-harmonic problem. The heuristics of the method are given and numerical computations illustrate the obtained accuracy.

In a forthcoming paper, we describe the magnetic potential in the vicinity of a corner of a conducting body embedded in a dielectric medium in a bidimensional setting. We make explicit the corner asymptotic expansion for this potential as the distance to the corner goes to zero. This expansion involves singular functions and singular coefficients. We introduce a method for the calculation of the singular functions near the corner and we provide two methods to compute the singular coefficients: the method of moments and the method of quasi-dual singular functions. Estimates for the convergence of both approximate methods are proven. We eventually illustrate the theoretical results with finite element computations. The specific non-standard feature of this problem lies in the structure of its singular functions: They have the form of series whose first terms

are harmonic polynomials and further terms are genuine non-smooth functions generated by the piecewise constant zeroth order term of the operator. This work has been presented in the international conference WCCM 2012.

6.2.11. Asymptotic models for penalization methods in porous media

Participants: Gilles Carbou, Victor Péron.

We investigate a Stokes-Brinkman problem with Beavers and Joseph transmission conditions, adapted to a penalization method in porous media. We exhibit a WKB expansion for the solution of the fluid-porous interface problem. The main interest is to derive equivalent models for the penalization method. We explicit the first terms of the WKB expansion for the flow and the pressure in the subdomains. Each asymptotics of the flow writes as a sum of a tangential boundary layer term plus a standard term in the porous region. From the benefits or these boundary layers, we infer a collection of elementary transmission problems satisfied by the standard parts of the asymptotics for the flow and the pressure. As a consequence of the penalization of the Laplacian operator which applies to the flow in the porous media, a degenerate operator of order zero applies to the elementary velocities appears in the porous region. The main difficulty concern the proof of elliptic regularity up to the interface for the solution of each elementary problem, since exotic conditions for the flow and the pressure appears along the interface. Our strategy consists to adapt a proof of elliptic regularity for the solution of a Darcy problem set in homogeneous media and developed by Boyer-Fabrie.

6.2.12. Asymptotic modeling in electromagnetism

Participants: Marc Duruflé, Victor Péron, Clair Poignard.

We investigate asymptotic models for 3D transmission problems in electromagnetism with homogeneous thin layers (uniform thickness). We exhibit Generalized Impedance Boundary Conditions of order 1 when the thin layer is symmetric and non-symmetric with respect to its mean surface. We present also a limit model for a resistive thin layer, and an equivalent model of order 1 for large contrast in conductivities through the thin layer. We write all these models in a general form. Questions regarding the implementation of the conditions have been addressed carefully. Numerical results with the high-order finite element library Montjoie illustrate the accuracy of the asymptotic models. A paper is in preparation.

6.2.13. Absorbing Boundary Conditions for Tilted Transverse Isotropic Elastic Media

Participants: Hélène Barucq, Lionel Boillot, Henri Calandra, Julien Diaz.

The simulation of wave propagation in geophysical media is often performed in domains which are huge compared to the wavelenghts of the problem. It is then necessary to reduce the computational domain to a box. When considering acoustic or elastic isotropic media, this can be done by applying an Absorbing Boundary Condition (ABC) or by adding a Perfectly Matched Layer (PML). However, a realistic representation of the Earth subsurface must include anisotropy and, in particular, the so-called Tilted Transverse Isotropy. Perfectly Matched Layers are known to be unstable for this kind of media and, to the best of our knowledge, no ABC have been proposed yet. We have thus proposed a low-order ABC for TTI media.

This ABC has been constructed for elliptic TTI media, where the slowness curve of the P-Wave is a rotated ellipse. Then, an appropriate change of variable can be applied in order to transform this ellipse into a circle. The main idea consists in imposing the isotropic ABC in the new system of coordinates and to apply the inverse change of variable in order to obtain the elliptic TTI ABC. We have compared numerically the reflections generated by this new ABC in TTI domain to the ones generated by the classical first order ABC in isotropic domains. The results show that the new ABC performs as well as the classical first order one. Moreover, this ABC seems to be also well-suited to non elliptic TTI media. These results have been presented at the Congrès Français d'Acoustique [35], at two workshops [39], [45].

6.2.14. Efficient solution methodology based on a local wave tracking strategy for high-frequency Helmholtz problems.

Participants: Mohamed Amara, Sharang Chaudhry, Julien Diaz, Rabia Djellouli, Steven Fiedler.

We have designed a new and efficient solution methodology for solving high-frequency Helmholtz problems. The proposed method is a least-squares based technique that employs variable bases of plane waves at the element level of the domain partition. A local wave tracking strategy is adopted for the selection of the basis at the regional/element level. More specifically, for each element of the mesh partition, a basis of plane waves is chosen so that one of the plane waves in the basis is oriented in the direction of the propagation of the field inside the considered element. The determination of the direction of the field inside the mesh partition is formulated as a minimization problem. Since the problem is nonlinear, we apply Newton's method to determine the minimum. The computation of Jacobians and Hessians that arise in the iterations of the Newton's method is based on the exact characterization of the Fréchet derivatives of the field with respect to the propagation directions. Such a characterization is crucial for the stability, fast convergence, and computational efficiency of the Newton algorithm. These results are part of the Master thesis of Sharang Chaudhry (student à CSUN) and have been presented to the 6th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS, Vienna, 2012).

6.3. High Performance methods for solving wave equations

Participants: Lionel Boillot, Hélène Barucq, Henri Calandra, Julien Diaz, Emiljana Jorgji, Didier Rémy, Florent Ventimiglia.

We have recently optimized the DG code implemented in the DIVA plateform of Total by reducing the number of communications between each processors. Since this code is based on the first order formulation of the elastodynamic wave equation, we have to compute three velocities and six stresses at each degree of freedom of the mesh. One naive idea consists in communicating these nine values at each time step. On the other hand, the computation of the three velocities does not actually require the knowledge of the six stresses but of three linear combination of these stresses. Similarly, the computation of the stresses requires the knowledge of six linear combinations of the three velocities. The main idea of the optimization consists in computing the three linear combinations of the stresses and to communicate them to the other processors, while the three velocities are communicated before computing the linear computations. Hence the number of communications can be reduced to six at each time step.

This optimization, coupled with the use of Hybrid MPI and OpenMP parallel programming has allowed to prove the scalability of the code up to 512 cores. We are now planning to extend these tests up to 4000 cores.

MAGNOME Project-Team

6. New Results

6.1. Yeast comparative genomics

Participants: Pascal Durrens [correspondant], Tiphaine Martin, David James Sherman.

By using MAGNOME's MAGUS system and YAGA software, we have successfully realized a full annotation and analysis of seven new genomes, provided to the Génolevures Consortium by the CEA–Génoscope (Évry)[15]. Two distant genomes from the *Debaryomycetaceae* and *mitosporic Saccharomycetales* clades of the *Saccharomycetales* were annotated using previously published Génolevures genomes [6], [10], [11] as references (in prep.). A further group of five species, comprised of pathogenic and nonpathogenic species, was analyzed with the goal of identifying virulence determinants [37]. By choosing species that are highly related but which differ in the particular traits that are targeted, in this case pathogenicity, we are able to focus of the few hundred genes related to the trait (in rev.). The approximately 40,000 new genes from these studies were classified into existing Génolevures families as well as branch-specific families.

In collaboration with partners in the ISVV, Bordeaux, we have assembled and analyzed 12 wine starter yeasts, with the goal of understanding genetic determinants of performance (in prep.).

6.2. Assembly, annotation and comparison of bacterial Omics data

Participants: Elisabeth Bon [correspondant], Laetitia Bourgeade, Pascal Durrens, Aurélie Goulielmakis, Tiphaine Martin, David James Sherman.

Oenococcus oeni is part of the natural microflora of wine and related environments, and is the main agent of the malolactic fermentation (MLF), a step of wine making that generally follows alcoholic fermentation (AF) and contributes to wine deacidification, improvement of sensorial properties and microbial stability. The start, duration and achievement of MLF are unpredictable since they depend both on the wine characteristics and on the properties of the *O. oeni* strains. In collaboration with Patrick Lucas's lab of the ISVV Bordeaux that is currently proceeding with genome sequencing, explorative and, and comparative genomics, Elisabeth Bon coordinates our efforts into the OENIKITA project (since 2009), a scale switching challenge including highthrouput exploratory and comparative genomics for oenological bacterial starters, and the development of an online web-collaborative multigenomic comparative platform based on the the Génolevures database architecture and MAGUS / YAGA systems.

OENI-Genomics: In comparative genomics, we investigated gene repertoire and genomic organization conservation through intra- and inter-species genomic comparisons, which clearly show that the *O. oeni* genome is highly plastic and fast-evolving. Results reveal that the optimal adaptation to wine of a strain mostly depends on the presence of key adaptive loops and polymorphic genes. They also point up the role of horizontal gene transfer and mobile genetic elements in O. oeni genome plasticity, and give the first clues of the genetic origin of its oenological aptitudes[3], [14], [29], [33], [35], [36]. As a result of the scaling out challenge, we participated to the assembly and annotation of 19 fully sequenced *O. oeni* genome variants.

KITA-Genomics (E. Bon, D. Sherman): This project that is focused on the sequencing, assembly, exploration and comparison of the *O. kitaharae* genome, has benefited to an international collaboration involving Dr V. Makeev. MAGNOME was involved into the pilot assembly, exploration and comparison of the *O. kitaharae* genome.

Transcriptomic axis (E. Bon, A. Goulielmakis, P. Durrens): Under the supervision of E. Bon, Aurélie Goulielmakis has completed for the ANR DIVOENI a detailed manual annotation of a new reference strain of *O. oeni* and performed comparative transcriptome analysis to identify genes differentially expressed under different culture conditions. We explored and compared how the expression system is solicited when *O. oeni* strains adapted to grow in some niches are placed under stress-exposure conditions. The monitoring of gene expression status between strains, through the definition of a global expression pattern proper to each gene, partially lift the veil on how *O. oeni* genome adapts function to its environment. The weight of genetic background and ecological niche pressure on gene expression flexibility was evaluated, and the *O. oeni* pan-transcriptome architecture characterized. The first guidelines revealed a supra-spatial organization of stress response into activated and repressed larger macro-domains defining functional landmarks and intra-chromosomal territories. Decryption of stress-sensitive gene repertoires promises to be an efficient tool in the conquest of *O. oeni* "domestication" through the identification of molecular markers responsible for different physiological capabilities, and the selection of the best adapted strains [21], [43].

Gene plasticity modelisation (E. Bon, L. Bourgeade): A novel axis of research recently emerged under the initiative of E. Bon (pseudOE project) around the detection, characterization and conservation of pseudogenes populations in *Oenococcus* bacteria. Such topic presents a double interest: phylogenetic at first because it should allow to better estimate the degree of genic/genomic plasticity of these bacteria, and algorithmic then because the pseudogenes are a source of confusion for the automatic prediction of genes. Through a transversal collaboration and a cooperative supervision with the Algorithms for Analysis of Biological Structures Group (P. Ferraro, J. Allali) at LaBRI, Laetitia Bourgeade (PhD, Univ. Bordeaux1) was recruited to develop dedicated methods to improve pseudogenes automatic detection, and therefore gene predictions, and to reconstruct fossil and modern genes evolutionary history [20], [23].

6.3. Big Data in comparative genomics

Participants: David James Sherman [correspondant], Pascal Durrens, Natalia Golenetskaya, Florian Lajus, Tiphaine Martin.

Data growth in comparative genomics presents a significant scaling challenge that requires novel informatic methods. Increase in sequence data is already a challenge, but in addition, the *relations* between the biological objects increase supralinearly (geometrically in the worst case) for every linear increase in sequence data.

MAGNOME's Tsvetok system proposes a highly-scalable distributed approach for data and computation in comparative genomics, targeting projects of the "comparative genomics of related species" type, where a set of genomes is sequenced and analyzed as part of the same process. Tsvetok combines a novel NoSQL storage schema with domain-specific MapReduce algorithms, to efficiently handle the fundamentally data-parallel analyses encountered in comparative genomics. Natalia Golenetskaya with Florian Lajus derived use cases from web site log analyses to identify standard queries, define an appropriate query-oriented storage schema, and map structured values to this schema. This was tested in MAGNOME's dedicated computing cluster.

Natalia Golenetskaya furthermore defined new distributed algorithms for two important large-scale analyses in MAGNOME's pipeline: systematic identification of gene fusion and fission events in eukaryote genomes (following [7]), and large-scale consensus clustering for protein families (following [9]). For fusions and fissions, she defined a new MapReduce algorithm that avoids graph-based analysis (which is notoriously slow in MapReduce), to achieve both significant speed ups and excellent scaling to much larger data sets. For protein family clustering, she defined a novel iterative sampling strategy that combines parallel clustering of submatrices of pairwise relations, to succesively approximate the result of a complete clustering, without the need to store the entire matrix of relations in memory.

6.4. Inferring metabolic models

Participants: David James Sherman [correspondant], Pascal Durrens, Razanne Issa, Anna Zhukova.

In collaboration with Prof Jean-Marc Nicaud's lab at the INRA Grignon, we developed the first functional genome-scale metabolic model of an oleaginous yeast. Most work in producing genome-scale metabolic models has focused on model organisms, in part due to the cost of obtaining well-annotated genome sequences and sufficiently complete experimental data for refining and verifying the models. However, for many fungal genomes of biotechnological interest, the combination of large-scale sequencing projects and in-depth experimental studies has made it feasible to undertake metabolic network reconstruction for a wider range of organisms.

An excellent representative of this new class of organisms is *Yarrowia lipolytica*, an oleaginous yeast studied experimentally for its role as a food contaminant and its use in bioremediation and cell factory applications. As one of the hemiascomycetous yeasts completely sequenced in the Génolevures program it enjoys a high quality manual annotation by a network of experts. It is also an ideal subject for studying the role of species-specific expansion of paralogous families, a considerable challenge for eukaryotes in genome-scale metabolic construction. To these ends, we undertook a complete reconstruction of the *Y. lipolytica* metabolic network.

Methods: A draft model was extrapolated from the *S. cerevisiae* model iIN800, using *in silico* methods including enzyme conservation predicted using Génolevures and reaction mapping maintaining compartments. This draft was curated by a group of experts in *Y. lipolytica* metabolism, and iteratively improved and validated through comparison with experimental data by flux balance analysis. Gap filling, species-specific reactions, and the addition of compartments with the corresponding transport reactions were among the improvements that most affected accuracy. These methods, initially implemented in an *ad hoc* way in the *Pathtastic* software tool, have been redefined and formalized by Razanne Issa using a novel logical framework.

Results: We produced an accurate functional model for *Y. lipolytica*, MODEL1111190000 in Biomodels.net, that has been qualitatively validated against gene knockouts. This model has been enriched by Anna Zhukova with ontology terms from ChEBI and GO.

6.5. Summarized visualization of metabolic models

Participants: David James Sherman [correspondant], Anna Zhukova.

In collaboration with Romain Bourqui and Antoine Lambert of the LaBRI, we defined new strategies for exploring whole genome metabolic models. There is an inherent tension between detail and understandability in these large networks: on the one hand, detailed description of individual reactions is needed for accurate simulation, but on the other hand, high-level views of reactions are needed for describing partways in human terms. We are defining knowledge-based simplification rules, that permit the user to factor similar reactions into one "generic" reaction in order to visualize a whole pathway or compartment, while maintaining the underlying model so that the user can later "drill down" to the specific reactions if need be. New layout rules implemented in the Tulip platform are used to draw the resulting networks in a familiar way.

In collaboration with Bruno Pinaud of the LaBRI, rule-based rewriting of metabolic models was used to define these simplifications using his PORGY software tool.

6.6. Hierarchical modeling with BioRica

Participants: David James Sherman [correspondant], Rodrigo Assar Cuevas, Nicolás Loira.

A recurring challenge for *in silico* modeling of cell behavior is that experimentally validated models are so focused in scope that it is difficult to repurpose them. Hierarchical modeling is one way of combining specific models into networks. Effective use of hierarchical models requires both formal definition of the semantics of such composition, and efficient simulation tools for exploring the large space of complex behaviors.

BioRica is a high-level hierarchical modeling framework for models combining continuous and discrete components. By providing a reliable and functional software tool backed by a rigorous semantics, we hope to advance real adoption of hierarchical modeling by the systems biology community. By providing an understandable and mathematically rigorous semantics, this will make is easier for practicing scientists to build practical and functional models of the systems they are studying, and concentrate their efforts on the system rather than on the tool.

Building on previous work that formalized strategies for integrating discrete control with continuous models, Rodrigo Assar defined a new framework for BioRica models using Kaufman's Quantized State Systems (in prep.).

MNEMOSYNE Team

6. New Results

6.1. Introduction

2012 is the year of birth of the Mnemosyne team; it is also a year of transition, since most of its members were previously in the Cortex project-team in Nancy. Accordingly, this year was partly devoted to ongoing projects in the Cortex team and to the initiation of the first activities in Mnemosyne. Apart from the results listed below, corresponding to the extension of current projects from the Cortex team to our new topics, we have also begun to study models of episodic and semantic memory at the interface between the hippocampus and the cortex and interaction between models of the basal ganglia and the prefrontal cortex.

6.2. Systemic view of visuomotor transformations

Visuomotricity was an important topic in our activities in the Cortex team. We are pursuing these activities in ongoing projects (particularly the ANR Keops project, cf. § 7.1), and extend them according to a systemic view, integrating new information flows from the external world and from other neuronal structures:

- We consider the role of non-standard cells in the retina [11], reported as responsible for fast event-detection in the visual flow.
- We have initiated a modeling study of the retina-thalamus-cortex information flow and particularly of its non-specific pathway [9] that can account for attentional mechanisms.

CEPAGE Project-Team

6. New Results

6.1. Resource allocation and Scheduling

6.1.1. Divisible Load Scheduling

Participants: Olivier Beaumont, Nicolas Bonichon, Lionel Eyraud-Dubois.

Malleable tasks are jobs that can be scheduled with preemptions on a varying number of resources. In [22], we focus on the special case of work-preserving malleable tasks, for which the area of the allocated resources does not depend on the allocation and is equal to the sequential processing time. Moreover, we assume that the number of resources allocated to each task at each time instant is bounded. We consider both the clairvoyant and non-clairvoyant cases, and we focus on minimizing the weighted sum of completion times. In the weighted non-clairvoyant case, we propose an approximation algorithm whose ratio (2) is the same as in the unweighted non-clairvoyant case. In the clairvoyant case, we provide a normal form for the schedule of such malleable tasks, and prove that any valid schedule can be turned into this normal form, based only on the completion times of the tasks. We show that in these normal form schedules, the number of preemptions per task is bounded by 3 on average. At last, we analyze the performance of greedy schedules, and prove that optimal schedules are greedy for a special case of homogeneous instances. We conjecture that there exists an optimal greedy schedule for all instances, which would greatly simplify the study of this problem. Finally, we explore the complexity of the problem restricted to homogeneous instances, which is still open despite its very simple expression. (Joint work with Loris Marchal from ENS Lyon)

6.1.2. Scheduling for Distributed Continuous Integration

Participants: Olivier Beaumont, Nicolas Bonichon, Ludovic Courtès.

In [21], we consider the problem of schedul- ing a special kind of mixed data-parallel applications arising in the context of continuous integration. Continuous integration (CI) is a software engineering technique, which consists in re- building and testing interdependent software components as soon as developers modify them. The CI tool is able to provide quick feedback to the developers, which allows them to fix the bug soon after it has been introduced. The CI process can be described as a DAG where nodes represent package build tasks, and edges represent dependencies among these packages; build tasks themselves can in turn be run in parallel. Thus, CI can be viewed as a mixed data-parallel application. A crucial point for a successful CI process is its ability to provide quick feedback. Thus, makespan minimization is the main goal. Our contribution is twofold. First, we provide and analyze a large dataset corresponding to a build DAG. Second, we compare the performance of several scheduling heuristics on this dataset.

6.1.3. Resource Allocation in Clouds

Participants: Olivier Beaumont, Lionel Eyraud-Dubois, Hejer Rejeb.

In [14], we consider the problem of assigning a set of clients with demands to a set of servers with capacities and degree constraints. The goal is to find an allocation such that the number of clients assigned to a server is smaller than the server's degree and their overall demand is smaller than the server's capacity, while maximizing the overall throughput. This problem has several natural applications in the context of independent tasks scheduling or virtual machines allocation. We consider both the *offline* (when clients are known beforehand) and the *online* (when clients can join and leave the system at any time) versions of the problem. We first show that the degree constraint on the maximal number of clients that a server can handle is realistic in many contexts. Then, our main contribution is to prove that even if it makes the allocation problem more difficult (NP-Complete), a very small additive resource augmentation on the servers degree is enough to find in polynomial time a solution that achieves at least the optimal throughput. After a set of theoretical results on the complexity of the offline and online versions of the problem, we propose several other greedy heuristics to solve the online problem and we compare the *performance* (in terms of throughput) and the *cost* (in terms of disconnections and reconnections) of all proposed algorithms through a set of extensive simulation results. (Joint work with Christopher Thraves-Caros, University of Madrid)

6.1.4. Non Linear Divisible Load Scheduling

Participants: Olivier Beaumont, Hubert Larchevêque.

Divisible Load Theory (DLT) has received a lot of attention in the past decade. A divisible load is a perfect parallel task, that can be split arbitrarily and executed in parallel on a set of possibly heterogeneous resources. The success of DLT is strongly related to the existence of many optimal resource allocation and scheduling algorithms, what strongly differs from general scheduling theory. Moreover, recently, close relationships have been underlined between DLT, that provides a fruitful theoretical framework for scheduling jobs on heterogeneous platforms, and MapReduce, that provides a simple and efficient programming framework to deploy applications on large scale distributed platforms. The success of both have suggested to extend their framework to non-linear complexity tasks. In [24], we show that both DLT and MapReduce are better suited to workloads with linear complexity. In particular, we prove that divisible load theory cannot directly be applied to quadratic workloads, such as it has been proposed recently. We precisely state the limits for classical DLT studies and we review and propose solutions based on a careful preparation of the dataset and clever data partitioning algorithms. In particular, through simulations, we show the possible impact of this approach on the volume of communications generated by MapReduce, in the context of Matrix Multiplication and Outer Product algorithms. (Joint work with Loris Marchal from ENS Lyon)

6.1.5. Reliable Service Allocation in Clouds

Participants: Olivier Beaumont, Lionel Eyraud-Dubois, Hubert Larchevêque.

In [23], we consider several reliability problems that arise when allocating applications to processing resources in a Cloud computing platform. More specifically, we assume on the one hand that each computing resource is associated to a capacity constraint and to a probability of failure. On the other hand, we assume that each service runs as a set of independent instances of identical Virtual Machines, and that the Service Level Agreement between the Cloud provider and the client states that a minimal number of instances of the service should run with a given probability. In this context, given the capacity and failure probabilities of the machines, and the capacity and reliability demands of the services, the question for the cloud provider is to find an allocation of the instances of the services (possibly using replication) onto machines satisfying all types of constraints during a given time period. The goal of this work is to assess the impact of the reliability constraint on the complexity of resource allocation problems. We consider several variants of this problem, depending on the number of services and whether their reliability demand is individual or global. We prove several fundamental complexity results (#P' and NP-completeness results) and we provide several optimal and approximation algorithms. In particular, we prove that a basic randomized allocation algorithm, that is easy to implement, provides optimal or quasi-optimal results in several contexts, and we show through simulations that it also achieves very good results in more general settings.

6.1.6. Optimizing Resource allocation while handling SLA violations in Cloud Computing platforms

Participants: Lionel Eyraud-Dubois, Hubert Larchevêque.

In [29], we study a resource allocation problem in the context of Cloud Computing, where a set of Virtual Machines (VM) has to be placed on a set of Physical Machines (PM). Each VM has a given demand (e.g. CPU demand), and each PM has a capacity. However, each VM only uses a fraction of its demand. The aim is to exploit the difference between the demand of the VM and its real utilization of the resources, to exploit the capacities of the PMs as much as possible. Moreover, the real consumption of the VMs can change over time (while staying under its original demand), implying sometimes expensive "SLA violations", corresponding to some VM's consumption not satisfied because of overloaded PMs. Thus, while optimizing the global resource utilization of the PMs, it is necessary to ensure that at any moment a VM's need evolves, a few number of migrations (moving a VM from PM to PM) is sufficient to find a new configuration in which all the VMs' consumptions are satisfied. We modelize this problem using a fully dynamic bin packing approach and we present an algorithm ensuring a global utilization of the resources of 66%. Moreover, each time a PM is overloaded at most one migration is necessary to fall back in a configuration with no overloaded PM, and only

3 different PMs are concerned by required migrations that may occur to keep the global resource utilization correct. This allows the platform to be highly resilient to a great number of changes.

6.2. Compact Routing

6.2.1. Compact routing with forbidden-set in planar graphs

Participant: Cyril Gavoille.

In [20], we consider fully dynamic $(1+\varepsilon)$ distance oracles and $(1+\varepsilon)$ forbidden-set labeling schemes for planar graphs. For a given n-vertex planar graph G with edge weights drawn from $[1, M]$ and parameter $\varepsilon > 0$, our forbidden-set labeling scheme uses labels of length $\lambda = O(\varepsilon^{-1} \log^2 n \log(nM) \cdot \max logn)$. Given the labels of two vertices s and t and of a set F of faulty vertices/edges, our scheme approximates the distance between s and t in $G \setminus F$ with stretch $(1+\varepsilon)$, in $O(|F|^2\lambda)$ time.

We then present a general method to transform $(1+\varepsilon)$ forbidden-set labeling schemas into a fully dynamic $(1+\varepsilon)$ distance oracle. Our fully dynamic $(1+\varepsilon)$ distance oracle is of size $O(n \log n \cdot \max logn)$ and has $\widetilde{O}(n^{1/2})$ query and update time, both the query and the update time are worst case. This improves on the best previously known $(1+\varepsilon)$ dynamic distance oracle for planar graphs, which has worst case query time $\widetilde{O}(n^{2/3})$ and amortized update time of $\widetilde{O}(n^{2/3})$.

Our $(1+\varepsilon)$ forbidden-set labeling scheme can also be extended into a forbidden-set labeled routing scheme with stretch $(1+\varepsilon)$.

6.2.2. Planar Spanner of geometric graphs

Participants: Nicolas Bonichon, Cyril Gavoille, Nicolas Hanusse.

In [26], we determine the stretch factor of L_1-Delaunay and L_∞-Delaunay triangulations, and we show that this stretch is $\sqrt{4+2\sqrt{2}} \approx 2.61$. Between any two points x, y of such triangulations, we construct a path whose length is no more than $\sqrt{4+2\sqrt{2}}$ times the Euclidean distance between x and y, and this bound is best possible. This definitively improves the 25-year old bound of $\sqrt{10}$ by Chew (SoCG '86).

To the best of our knowledge, this is the first time the stretch factor of the well-studied L_p-Delaunay triangulations, for any real $p \geq 1$, is determined exactly.

6.3. Mobile Agents

6.3.1. More efficient periodic traversal in anonymous undirected graphs

Participants: David Ilcinkas, Ralf Klasing.

In [15], we consider the problem of *periodic graph exploration* in which a mobile entity with constant memory, *an agent*, has to visit all n nodes of an input simple, connected, undirected graph in a periodic manner. Graphs are assumed to be anonymous, that is, nodes are unlabeled. While visiting a node, the agent may distinguish between the edges incident to it; for each node v, the endpoints of the edges incident to v are uniquely identified by different integer labels called *port numbers*. We are interested in algorithms for assigning the port numbers together with traversal algorithms for agents using these port numbers to obtain short traversal periods.

Periodic graph exploration is unsolvable if the port numbers are set arbitrarily; see Budach (1978). However, surprisingly small periods can be achieved by carefully assigning the port numbers. Dobrev *et al.* (2005) described an algorithm for assigning port numbers and an oblivious agent (i.e., an agent with no memory) using it, such that the agent explores any graph with n nodes within the period $10n$. When the agent has access to a constant number of memory bits, the optimal length of the period was proved in Gasieniec *et al.* (2008) to be no more than $3.75n - 2$ (using a different assignment of the port numbers and a different traversal algorithm). In our work, we improve both these bounds. More precisely, we show how to achieve a period length of at most $(4+\frac{1}{3})n - 4$ for oblivious agents and a period length of at most $3.5n - 2$ for agents with constant memory. To obtain our results, we introduce a new, fast graph decomposition technique called a *three-layer partition* that may also be useful for solving other graph problems in the future. Finally, we present the first non-trivial lower bound, $2.8n - 2$, on the period length for the oblivious case.

6.3.2. Gathering of Robots on Anonymous Grids without Multiplicity Detection

Participant: Ralf Klasing.

In [28] , we study the gathering problem on grid networks. A team of robots placed at different nodes of a grid have to meet at some node and remain there. Robots operate in Look-Compute-Move cycles; in one cycle, a robot perceives the current configuration in terms of occupied nodes (Look), decides whether to move towards one of its neighbors (Compute), and in the positive case makes the computed move instantaneously (Move). Cycles are performed asynchronously for each robot. The problem has been deeply studied for the case of ring networks. However, the known techniques used on rings cannot be directly extended to grids. Moreover, on rings, another assumption concerning the so-called *multiplicity detection* capability was required in order to accomplish the gathering task. That is, a robot is able to detect during its Look operation whether a node is empty, or occupied by one robot, or occupied by an undefined number of robots greater than one.

In our work, we provide a full characterization about gatherable configurations for grids. In particular, we show that in this case, the multiplicity detection is not required. Very interestingly, sometimes the problem appears trivial, as it is for the case of grids with both odd sides, while sometimes the involved techniques require new insights with respect to the well-studied ring case. Moreover, our results reveal the importance of a structure like the grid that allows to overcome the multiplicity detection with respect to the ring case.

HIEPACS Project-Team

6. New Results

6.1. Algorithms and high-performance solvers

6.1.1. Dense linear algebra solvers for multicore processors accelerated with multiple GPUs

In collaboration with the Inria RUNTIME team and the University of Tennessee, we have designed dense linear algebra solvers that can fully exploit a node composed of a multicore processor accelerated with multiple GPUs. This work has been integrated in the latest release of the MAGMA package (http://icl.cs.utk.edu/magma/). We have used the StarPU runtime system to ensure the portability of our algorithms and codes. We have also investigated the case of partial pivoting LU factorization. The pivot selection induces a large number of low granularity tasks which are a potential bottleneck when handled with a runtime system; we have thus designed methods which aim at limiting the number of tasks.

6.1.2. Task-based Conjugate-Gradient for multi-GPUs platforms

Whereas most today parallel High Performance Computing (HPC) software is written as highly tuned code taking care of low-level details, the advent of the manycore area forces the community to consider modular programming paradigms and delegate part of the work to a third party software. That latter approach has been shown to be very productive and efficient with regular algorithms, such as dense linear algebra solvers. In this paper we show that such a model can be efficiently applied to a much more irregular and less compute intensive algorithm. We illustrate our discussion with the standard unpreconditioned Conjugate Gradient (CG) that we carefully express as a task-based algorithm. We use the StarPU runtime system to assess the efficiency of the approach on a computational platform consisting of three NVIDIA Fermi GPUs. We show that almost optimum speed up (up to 2.89) may be reached (relatively to a mono-GPU execution) when processing large matrices and that the performance is portable when changing the low-level memory transfer mechanism. This work is developed in the framework of the PhD of Stojce Nakov.

6.1.3. Resilience in numerical simulations

Various interpolations strategies to handle restarting Krylov subspace methods in case of core faults have been investigated. The underlying idea is to recover fault entries of the iterate via interpolation from existing values available on neighbor cores. In particular, we design a scheme that enables to preserve the key property of GMRES that is the residual norm monotonicity of the iterates even when failures occur. This work is developed in the framework of Mawussi Zounon's PhD funded by the ANR-RESCUE. Notice that theses activities are also part of our contribution to the G8-ECS (Enabling Climate Simulation at extreme scale).

6.1.4. Block GMRES method with inexact breakdowns and deflated restarting

We have considered the solution of large linear systems with multiple right-hand sides using a block GMRES approach. We designed a new algorithm that effectively handles the situation of almost rank deficient block generated by the block Arnoldi procedure and that enables the recycling of spectral information at restart. The first feature is inherited from an algorithm introduced by Robbé and Sadkane [M. Robbé and M. Sadkane. Exact and inexact breakdowns in the block gmres method. Linear Algebra and its Applications, 419: 265-285, 2006.], while the second one is obtained by extending the deflated restarting strategy proposed by Morgan [R. B. Morgan. Restarted block GMRES with deflation of eigenvalues. Applied Numerical Mathematics, 54(2): 222-236, 2005.]. Through numerical experiments, we have shown that the new algorithm combines the attractive numerical features of its two parents that it outperforms. This work was developed in the framework of the post-doc position of Yan-Fei Jing.

6.1.5. Scalable numerical schemes for scientific applications

For the solution of the elastodynamic equation on meshes with local refinments, we are currently collaborating with Total to design a parallel implementation of a local time refinement technique on top of a discontinuous Galerkin space discretization. This latter technique enables to manage non-conforming meshes suited to deal with multiblock approaches that capture the locally refined regions. this work is developed in the framework of Yohann Dudouit PhD thesis. Perfectly Matched Layers has been designed to cope with the designed numerical scheme and a software prototype for 2D simulation has been implemented.

The calculation of acoustic modes in combustion chambers is a challenging calculation for large 3D geometries. It requires the parallel calculation of a few of the smallest eigenpairs of large unsymmetric matrices in a nonlinear iterative scheme. Various numerical techniques have been considered to attempt recycling spectral information from one nonlinear step to the next that includes Jacobi-Davidson, Krylov-Schur and block Krylov-Schur algorithms. This is part of the PhD research activity of Pablo Salas.

6.1.6. Fast Multipole Methods

Concerning the Fast Multipole Method, our prototype called ScalFMM was completely rewritten in order to easily add new features. There is two main parts: the management of the octree and the parallelization of the method and kernels. This new architecture allow us to easily add new FMM algorithm or kernels and new paradigm of parallelization. The limitation of the classical FMM was that we need all operators (P2M, M2M, M2L, L2L, L2P) on the multipole expansions if we want to add a new kernel. To overcome this and in the context of associated team FastLA, we introduced the black-box FMM algorithm that allow us to be now kernel independent.

6.1.6.1. Optimizations for the M2L operator of the Chebyshev Fast Multipole Method

Most Fast Multipole Methods (FMM) have been developed and optimized for specific kernel functions. Our goal is to improve the efficiency of an FMM that is kernel function independent. The formulation is based on a Chebyshev interpolation scheme and has been studied for asymptotically smooth kernel functions G(x,y) and also for oscillatory ones, such as K(x,y) = G(x,y) exp(ik|x-y|). Two weak points of this formulation are the expensive precomputation of the M2L operators and the higher computational intensity compared to other FMMs. We focused our recent research on these issues. We have come up with a set of optimizations that exploit symmetries far-field interactions and blocking schemes that pave the road for highly optimized matrix-matrix product implementations. Recall, the scope of the FMM as an algorithm to perform fast matrix-vector products (Ax = y) may be twofold: on one hand the result (y) and on the other hand the solution (x). A fast precomputation is crucial in the first and fast running times in the second case. We proposed optimizations that provide more than 1000 times faster precomputation, much less memory requirement and much faster running times than before. All these results are submitted in Journal of computational Physics [27].

6.1.6.2. Pipelining the Chebyshev Fast Multipole Method over a runtime system

Fast Multipole Method are a fundamental operation for the simulation of many physical problems. The high performance design of such methods usually requires to carefully tune the algorithm for both the targeted physics and the hardware. For the Chebyshev Fast Multipole Method (black-box FMM) we have proposed a new approach that achieves high performance across heterogeneous architectures. Our method consists of expressing the Fast Multipole Method algorithm as a task flow and employing a state-of-the-art runtime system, StarPU, in order to process the tasks on the different processing units. We carefully design the task flow, the mathematical operators, their Central Processing Unit (CPU) and Graphics Processing Unit (GPU) implementations, as well as scheduling schemes. We compute potentials and forces of 200 million particles in 48.7 seconds on a homogeneous 160 cores SGI Altix UV 100 and of 30 million particles in 10.9 seconds on a heterogeneous 12 cores Intel Nehalem processor enhanced with 3 Nvidia M2090 Fermi GPUs. All these results are available in [24].

6.2. Efficient algorithmics for code coupling in complex simulations

Dynamic load balancing is an important step conditioning the performance of parallel adaptive codes whose load evolution is difficult to predict. Most of the studies which answer this problem perform well, but are limited to an initially fixed number of processors which is not modified at runtime. These approaches can be very inefficient, especially in terms of resource consumption, as demonstrated by Iqbal et al. As computation progresses, the global workload may increase drastically, exceeding memory limit for instance. In such a case, we argue it should be relevant to adjust the number of processors while maintaining the load balanced. However, this is still an open question that we currently focus on.

To overcome this issue, we propose a new graph repartitioning algorithm, which accepts a variable number of processors, assuming the load is already balanced. We call this problem the $M \times N$ graph repartitioning problem, with M the number of former parts and N the number of newer parts. Our algorithm minimizes both data communication (i.e., cut size) and data migration overheads, while maintaining the computational load balance in parallel. This algorithm is based on a theoretical result, that constructs optimal communication matrices with both a minimum migration volume and a minimum number of communications. It uses recent graph/hypergraph partitioning techniques with fixed vertices in a similar way than the one used in Zoltan for dynamic load-balancing of adaptive simulations. We validate this work for a large variety of real-life graphs (i.e., university of Florida sparse matrix collection), comparing it against state-of-the-art partitioners (Metis, Scotch, Zoltan).

We are considering several perspectives to our work. First, we focus on graph repartitioning in the more general case where both the load and the number of processors vary. We expect this work to be really suitable for next generation of adaptive codes. Finally, to be useful in real-life applications, our algorithm needs to work in parallel, that mainly requires to use a direct *k-way* parallel partitioning software that handle fixed vertices, like *Scotch*. This should allow us to partition much larger graph in larger part number. As another perspective, this approach can be relevant in the context of code coupling: e.g., if one code becomes more computationally intensive relatively to the other, it could be valuable to dynamically migrate some processor resources to the other code, and thus to equilibrate the whole coupled application. This work is currently conducted in the framework of Clément Vuchener PhD thesis and should be defended in september 2013.

6.3. Distributed Shared Memory approach for the steering of parallel simulations

As a different approach of EPSN, we recently propose in the thesis of J. Soumagne *an in-situ visualization approach for parallel coupling and steering of simulations through distributed shared memory files (DSM)*. Indeed, as simulation codes become more powerful and more interactive, it is desirable to monitor a simulation in-situ, performing not only visualization but also analysis of the incoming data as it is generated. Monitoring or post-processing simulation data in-situ has obvious advantage over the conventional approach of saving to – and reloading data from – the file system; the time and space it takes to write and then read the data from disk is a significant bottleneck for both the simulation and subsequent post-processing steps. Furthermore, the simulation may be stopped, modified, or potentially steered, thus conserving CPU resources.

In this thesis, we propose a loosely coupled approach that enables a simulation to transfer data to a visualization server via the use of in-memory files. We show in this study how the interface, implemented on top of a widely used hierarchical data format (HDF5), allows us to efficiently decrease the I/O bottleneck by using efficient communication and data mapping strategies. For steering, we present an interface that allows not only simple parameter changes but also complete re-meshing of grids or operations involving regeneration of field values over the entire computational domain to be carried out. This approach is generic enough so that no particular knowledge of the underlying model is required and a user can therefore plug any simulation to this framework without any re-compilation work.

A scalability study have demonstrated the performance of this solution up to 2048 cores on a Cray machine. Finally, the environment has been validated on two industrial test cases: the first one is developed by Ecole Centrale de Nantes and HydrOcean and an object placed into a wave maker is dynamically modified and steered, thereby making use of the re-meshing capabilities introduced by the framework; and the other is

developed by Ecole Centrale de Lyon and ANDRITZ HYDRO, a Pelton turbine is dynamically controlled and results are analyzed in-situ.

This thesis has been defended by J. Soumagne in december 2012. This work was supported by NextMuSE project receiving funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement 225967. It has been realized in collaboration with the Swiss National Supercomputing Centre (CSCS). J.

6.4. Material physics

6.4.1. Hybrid materials

The study of hybrid materials based on a coupling between molecular dynamics (MD) and quantum mechanism (QM) simulation has been conducted in collaboration with IPREM (Pau) within the ANR CIS 2007 NOSSI (ended December 2011). These simulations are complex and costly and may involve several length scales, quantum effects, components of different kinds (mineral-organic, hydro-philic and -phobic parts). Our goal was to compute dynamical properties of hybrid materials like optical spectra. The computation of optical spectra of molecules and solids is the most consuming time in such coupling. This requires new methods designed for predicting excited states and new algorithms for implementing them. Several tracks have been investigated in the project and new results obtained as described bellow.

Optical spectra.

Some new improvements in our TD-DFT code have been introduced. Our method is based on the LCAO method for densities and excited states that computes electronic excitation spectra. We have worked in two directions:

- As the method introduces a regularization parameter to obtain regularized spectra we have used it to build better algorithms. In particular, we have developed a new hierarchical algorithm that builds a well adapted frequency distribution to better capture the biggest peaks (strongest oscillator strengths) in the spectrum. Moreover, a nonlinear fit method was added and used to compute the transitions and the oscillator strengths of the spectrum.
- In our algorithm, we used a coarse grain paradigm to parallelize the spectrum computation. This approach leads to a memory bottleneck for large systems. In that respect, we have explored a new parallel approach based on a fine grain paradigm (matrix-vector parallelization) to better exploit the manycore architecture of the emerging computers.

Finally, the code called *fast*, is released of the inria's gforge.

QM/MM algorithm. For structure studies or dynamical properties, we have coupled QM model based on pseudo-potentials (SIESTA code) with dynamic molecular (DL-POLY code). Therefore we have developed a new algorithm to avoid accounting twice for the forces and the quantum electric field in the molecular model. All algorithms involved in the coupling have been introduced both in SIESTA and in DL-POLY codes. The following new developments needed by the coupling have been introduced in the SIESTA code:

- We have implemented a fast evaluation of the molecular electrostatic field on the quantum grid.
- We have introduced a non periodic Poisson solver based on the parallel linear Hypre solver. This solver allows us to use computation domains as small as possible.
- We have implemented the ElectroStatic Potential (ESP) fit method to obtain more physical point charges than those given by SIESTA with the Mulliken method. These point charges are used by the MM codes to compute electrostatic forces.

Thanks to all our developments introduced in SIESTA a collaboration with the SIESTA research team has started. This enables us to have access to their private svn like repository. Preliminary results on a water dimer and a water box systems show good agreement with other methods developed in SIESTA and DL-POLY teams.

these results were presented in [29], [30].

6.4.2. Material failures

We have started in the context of the OPTIDIS ANR to work on dislocation simulations. The main characteristic of these simulations is that they are highly dynamical. This year, we focused on the definition of efficient cache aware data structure to manage points and segments. All the algorithms have been adapted to this structure and we have stared the development of the OPTIDIS prototype. This prototype has been parallelized with OpenMP model. More physics will be added by our partners that will give us the capability to grow our simulation and run some meaningful benchmark.

We will work in three directions. Firstly, we will investigate how to adapt our fast multipole method to compute constraints and then forces in the context of FastLA associated team. Secondly, we will improved the displacement of the segments and the way to treat collision in parallel. Finally, we will move on hybrid parallelism for our prototype.

PHOENIX Project-Team

6. New Results

6.1. Design-driven Testing by simulation

Previously, we have introduced a paradigm-oriented development approach that revolves around a conceptual framework concretized by a design language [26]. A design description is used to generate high-level programming support, to perform a range of verifications, and to abstract over underlying technologies.

This approach is illustrated with the Sense-Compute-Control (SCC) paradigm [48], where an SCC software system gathers information about an environment via sensors (whether hardware or software) and issues orders to impact the environment via actuators. The SCC paradigm has a wide spectrum of applicability; we have used it successfully in the domains of home/building automation, multimedia, avionics and networking.

SCC systems involve both software concerns, like any software system, and integration concerns, for the constituent networked entities forming the environment of the SCC-loop. This situation is problematic for testing because it requires acquiring, testing and interfacing a variety of software and hardware entities. This process can rapidly become costly and time-consuming when the target environment involves many entities.

We have developed a simulation approach and a tool named *DiaSim* that leverage the DiaSpec description of an environment [15]. This description is used to generate both a programming framework to develop the simulation logic and an emulation layer to execute applications. The generic nature of our approach has been illustrated by leveraging two different simulation tools, namely, Siafu for 2-D rendering of home/building spaces, and FlightGear for avionics.

To fuel the simulation of an environment with accurate stimuli, we need to model real systems, including natural phenomena (*e.g.,* heat transfer in a building) or mechanical systems (*e.g.,* aircraft models). These physical models are typically defined as continuous systems using differential equations. To facilitate the reuse of off-the-shelf physical models, we have used a DSL named Acumen for describing differential equations. Acumen continuous models are coupled with the DiaSim discrete simulator, forming a hybrid system fueled by accurate stimulus producers [18].

These major accomplishments were conducted by Julien Bruneau, in the context of his PhD studies [11].

6.2. Design-driven Development of Dependable Software Systems

Dependability of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable [22]. This generic concept includes attributes such as availability, integrity and reliability. Dependable systems are now pervasive in a range of domains (*e.g.,* railway, avionics, automotive) and require a certification process. The main goal of certification is to demonstrate that a system is conform to its *high-level requirements*, resulting from functional and safety analyses.

Software plays an increasingly important role in dependable systems; software development is thus required to be certified. In particular, the stakeholders have to pay attention to the coherence of the functional and non-functional aspects of an application to demonstrate the conformance of the software with the high-level requirements. Non-functional aspects of a system refer to constraints on the manner in which this system implements and delivers its functionality (*e.g.,* performance, reliability, security) [48].
Coherence. Because functional and non-functional aspects are inherently coupled, ensuring their coherence is critical to avoid unpredicted failures [39]. For example, fault-tolerance mechanisms may significantly deteriorate the application performance. Generally, this kind of issues are detected at the late stages of the development process, increasing the development cost of applications [21].
Conformance. Ensuring that an application is in conformance with its high-level requirements is typically done by tracing their propagation across the development stages. In practice, this process is human-intensive and error prone because it is performed manually [37].

Certifying a development process requires a variety of activities. In industry, the usual procedures involve holding peer review sessions for coherence verification, and writing traceability documents for conformance certification. In this context, *design-driven development* approaches are of paramount importance because the design drives the development of the application and provides a basis for tracing requirements [53]. However, because most existing approaches are general purpose, their guidance is limited, causing inconsistencies to be introduced in the design and along the development process. This situation calls for an integrated development process centered around a conceptual framework that allows to guide the certification process in a systematic manner. In response to this situation, we proposed a design-driven development methodology, named DIASUITE [2], which is dedicated to the *Sense/Compute/Control (SCC) paradigm* [48]. As demonstrated by Shaw, the use of a specific paradigm provides a conceptual framework, leading to a more disciplined engineering process and guiding the verification process [47]. An SCC application is one that interacts with a physical environment. Such applications are typical of domains such as home/building automation, robotics and avionics.

In this work, we have shown the benefits of DIASUITE for the development of dependable SCC applications. This approach is applied to a realistic case study in the avionics domain, in the context of two non-functional aspects, namely time-related performance and reliability. The DIASUITE design language, named DIASPEC , offers declarations covering both functional and non-functional dimensions of an SCC application [2], [9] [32]. However, so far, the DIASUITE methodology has only been used to study each dimension in isolation, leaving open the problems of coherence and conformance when considering multiple dimensions. This work integrates all these dimensions, enabling the generation of validation support. More precisely, this work makes the following contributions:
Design coherence over functional and non-functional dimensions. We use the DIASPEC language to describe both functional and non-functional aspects of an application and apply this approach to a realistic case study. A DIASPEC description is verified at design time for coherence of its declarations. This verification is performed with respect to a formal model generated from a DIASPEC description.
Design conformance through the development process. At design time, we provide verification support to check the conformance between the specification and the formalized form of the high-level requirements. At implementation time, we guarantee the conformance between the application code and the previously verified requirements. This process is automatically done by leveraging the generative approach of DIASUITE . As some of the high-level requirements cannot be ensured at design time (*e.g.,* time-related performance), we provide further testing support to validate the implementation with respect to these remaining requirements. This support leverages a realistic flight simulator, namely FlightGear [44].
Validation in avionics. We validate our approach by developing a realistic case study in avionics. Following the DIASUITE methodology, we have developed an aircraft flight guidance system and tested it on FlightGear. Additionally, we have duplicated this case study in the context of a commercial drone system, namely Parrot AR.Drone. [2]

These accomplishments were conducted by Julien Bruneau, Quentin Enard and Stéphanie Gatti, in the context of their PhD studies. This work will be published at the International Conference on Pervasive and Embedded Computing and Computation Systems (PECCS'13).

6.3. Putting DiaSuite to Work

A continuing concern of the Phoenix research group is to put our work into practice by tackling realistic applications. We have validated DiaSuite on a variety of applications in areas including telecommunications, pervasive computing, and avionics.

Our expertise in smart home and building, combined with the maturity of DiaSuite, have given rise to the development of a dedicated instance of our technology called DiaSuiteBox. This instance is destined for technology transfer.

[2] http://ardrone.parrot.com

6.3.1. Applying DiaSuite to a Variety of Areas.

Let us examine the application of DiaSuite to two key areas: pervasive computing and avionics. In each case, demonstrations and posters have been presented to researchers and industrial partners [24], [25], [23], [35]

Smart Homes. Despite much progress, developing a pervasive computing application remains a challenge because of a lack of conceptual frameworks and supporting tools. This challenge involves coping with heterogeneous entities, overcoming the intricacies of distributed systems technologies, working out an architecture for the application, encoding it in a program, writing specific code to test the application, and finally deploying it.

At the beginning of this evaluation period, our research group was mainly interested in orchestrating applications in the telecommunications domain, leveraging new opportunities created by the emergence of Voice over IP (mainly based on SIP). Concurrently, a myriad of objects became networked, prompting a need to expand the scope of telecommunications beyond human-human interaction.

Two main industrial collaborations were instrumental to explore the scope of this evolution and to validate the Diasuite approach with realistic case studies. First, we collaborated with a French telecommunications company, in a two-year project named HomeSIP, to study the convergence between VoIP and networked objects in the context of home automation. During this project, we developed a range of applications, including remote appliance control through phone keypad, TV recording via SMS, and dynamic entry phone systems. Second, we contributed to a two-year project named SmartImmo, which gathered major French companies in the area of building construction, installation, and management. The goal of this project was to create a service infrastructure for building automation. SmartImmo gave us the opportunity to elaborate realistic building automation scenarios (*e.g.,* parking lot management, meeting room reservation, energy monitoring).

Our work on applying DiaSuite to the pervasive computing domain has leveraged key contributions by two PhD students of Phoenix, namely, Wilfried Jouve [36] and Nicolas Palix [42]. They both defended at the beginning of this evaluation period.

Avionics. Safety-critical applications have to fulfill stringent requirements, both functional and non-functional. These requirements have to be coherent with each other and must be preserved throughout the software development process. In this context, a design-driven development approach can play a critical role. However existing design-driven development approaches are often general purpose, providing little, if any, conceptual framework to guide the development. Previously, we explained how the DiaSuite approach was enriched with non-functional declarations such as QoS and error handing.

To validate the interest of DiaSuite for safety-critical applications, several avionics case studies have been realized in the context of a collaboration with Thales, a French airborne systems company. One case study was a flight guidance application; it is in charge of the plane navigation and is under the supervision of the pilot. For example, if the pilot specifies a heading to follow, the application compares it to the current heading, sensed by devices such as the Inertial Reference Unit, and maneuvers ailerons accordingly. To test this application, we have used the DiaSim tool coupled with the FlightGear simulator. A flight guidance application has also been developed for a commercial drone platform. The goal of this application was to make the drone autonomous by following a flight plan similar to the one in avionics.

This simulation work has been presented in the thesis of Julien Bruneau [11]. Non-functional concerns addressing error handling and QoS will be presented in two forthcoming dissertations.

6.3.2. DiaSuiteBox: an Ongoing Technology-Transfer Project.

The DiaSuiteBox platform runs an open-ended set of applications, leveraging a range of appliances and web services. Our solution consists of a dedicated development environment, an application store, and a lightweight runtime platform. This solution is based on DiaSuite.

DiaSuiteBox consists of three main components:

- A tool-based environment is dedicated to the development of applications, orchestrating networked entities. This environment leverages DiaSpec, its compiler and an Eclipse plugin.
- An application store is composed of two servers: (1) a server verifies and packages submitted applications of developers prior to making them available to users and (2) another server enables users to browse, select and install applications.
- An execution environment runs end-user applications and allows to manage and configure all aspects of a smart space. This environment can either be deployed on low-resource computing platform (*e.g.,* Plug-PC, set-top-box) at the end-user's home or in the Cloud, coupled with a gateway for controlling equipments on the end-user's side.

Thanks to the application store and a developer community, the platform should provide users with a stream of innovative applications. During the submission process, an application is automatically analyzed and checked in order to be certified. [3] The user is ensured that the behavior of its applications is innocuous and conform to their description. DiaSuiteBox supports several technology standards like UPnP, Bluetooth, USB...This platform can be easily extended by plugging appliances directly on the hardware platform or by connecting devices on the local network.

[3] This certification process is preliminary in the current version of DiaSuiteBox.

RUNTIME Project-Team

6. New Results

6.1. Mastering Heterogeneous Platforms

Participants: Cedric Augonnet, Olivier Aumage, Nicolas Collin, Ludovic Courtès, Nathalie Furmento, Sylvain Henry, Andra Hugo, Raymond Namyst, Cyril Roelandt, Corentin Rossignon, Ludovic Stordeur, Samuel Thibault, Pierre-André Wacrenier.

- We continued our work on extending StarPU to master exploitation of Heterogeneous Platforms.
- We have released version 1.0.0 of StarPU, now really considered a stable project that a lot of collaborators can base their work on.
- We have extended our lightweight DSM over MPI to support caching data [17], which dramatically reduces data transfers for classical applications.
- We have extended the StarPU scheduler to let the application provide several implementations of a function for the same architecture, implementation choice being performed by the scheduler according to actually measured performance, energy consumption, etc.
- We have collaborated with Computer Graphics research team in the MediaGPU project to make it possible to directly graphically render results from StarPU computations.
- Work has been initiated to integrate StarPU and SimGrid for the SONGS project, which will allow to simulate application execution on heterogeneous architectures, and thus easily experiment with scheduling strategies.
- We have extended StarPU with a protocol that permits to make it run with a master-slave model, which allowed to easily port it to the Intel SCC and Intel Xeon Phi processors, and will allow an easy load balancing support over MPI.
- We have extended StarPU to allow multiple parallel codes to run concurrently with minimal interference. Such parallel codes run within *scheduling contexts* that provide confined execution environments which can be used to partition computing resources. Scheduling contexts can be dynamically resized to optimize the allocation of computing resources among concurrently running libraries. We introduced a *hypervisor* that automatically expands or shrinks contexts using feedback from the runtime system (e.g. resource utilization).

  We demonstrated the relevance of our approach using benchmarks invoking multiple high performance linear algebra kernels simultaneously on top of heterogeneous multicore machines. We showed that our mechanism can dramatically improve the overall application run time (-34%), most notably by reducing the average cache miss ratio (-50%).
- We have improved [15] the OpenCL implementation on top of StarPU (SOCL) to allow applications to use StarPU's scheduling contexts through OpenCL's contexts and to explicitly schedule some kernels to enhance performance. Moreover, SOCL fully supports the OpenCL ICD extension and can now be dynamically selected amongst other available platforms which makes it easier to use.
- We have continued collaborations on applications on top of StarPU with the University of Mons [14], the University of Vienna [20], the University of Linköping, the University of Tsukuba, TOTAL, the CEA INAC in Grenoble and the BRGM French public institution in Earth science applications.
- In a joint work with French SME company CAPS entreprise, as part of the ANR ProHMPT project, we have demonstrated a proof of concept framework enabling three kinds of pieces of applicative code — a native StarPU code, a Magma/StarPU code and a HMPP/StarPU code annotated with HMPP's directives — to integrate and cooperate together on a computation as a single coherent application.

- As part of the HPC-GA project, we initiated a preliminary study with University of Rio Grande do Sul (UFRGS), Brazil, to cooperate on the modeling of common computing kernel tasks and potentially making use of kernel models designed at UFRGS within the StarPU's task cost evaluation framework.
- As part of the partnership with Total, and in relationship with StarPU's task scheduling work, we have explored solutions to semi-automatically adapt the grain of elementary tasks to the available computing resources.

6.2. High-Performance Intra-node Collective Operations

Participant: Brice Goglin.

- KNEM is known to improve the performance of point-to-point intra-node MPI communication significantly [13].
- We designed an extended RMA interface in KNEM that suits the needs of point-to-point, collective and RMA operations.
- We showed that the native use of KNEM in MPI collective implementations enabled further optimization by combining the knowledge of collective algorithms with the mastering of KNEM region management and copies.
- This work was initiated in the context of our collaboration with the MPICH2 team and is now also pursued within the OPEN MPI project in collaboration with the University of Tennessee in Knoxville.

6.3. Process Placement and Topology-Aware Computing

Participants: Emmanuel Jeannot, Guillaume Mercier, François Tessier.

- TREEMATCH's limitations have been addressed. In particular, it is now able to handle unbalanced physical topologies.
- TREEMATCH has been compared to various competitors. We carried out various experiments that showed that TREEMATCH outperforms other solutions based on graph partitioning or graph embedding. These experiments also showed the limitations of some existing solutions (Scotch for instance).
- TREEMATCH has been integrated into several major parallel programming environments. It is implemented as a load-balancer in Charm++ (François TESSIER made severals at UI Urbana Champaign) and is used to enhance topology management routines in Open MPI and MPICH2. It is indeed employed to allow rank reordering in functions such as `MPI_Dist_graph_create` for instance. This work started with a visit at UTK by Guillaume MERCIER.
- We set-up several collaborations: besides the collaboration with the Open MPI group, we also work with the CERFACS in order to speed-up existing CFD parallel applications developed by this group.

6.4. Thread placement and memory allocation on NUMA machines

Participant: Emmanuel Jeannot.

We have worked on optimizing the tiled Cholesky factorization on NUMA machine. We have designed a new symbolic technnique for allocating task and tiles at the same time called SMA (Symbolic Mapping and Allocation). SMA provide an optimal allocation in terms of point-to-point communication for the Cholesky factorization. We have studied some performance issues regarding the way threads are grouped and tiles are allocated in the memory. We have shown how to optimize thread placement and data placement in order to achieve performance gain up to 50% compared to state-of-the-art libraries such as Plasma or MKL. This work has been published in PAAP 2012 [25].

6.5. Scheduling for System On Chip

Participants: Paul-Antoine Arras, Emmanuel Jeannot, Samuel Thibault.

Today's embedded applications are increasingly demanding in terms of computational power, especially in real-time digital signal processing (DSP) where tight timing requirements are to be fulfilled. More specifically, when it comes to video decoding (e.g. H.264/AVC and HEVC) not only has it been almost impossible for some time to run such codecs on a stand-alone embedded processor, but it now also becomes quite impractical to execute them on homogeneous multicore platforms. In this context, STMicroelectronics is developing a scalable heterogeneous system-on-chip template called STHORM and aimed at meeting the latest codecs' requirements.

This year, we focused on the memory constraints embedded systems are subject to. As video coding is rather demanding in terms of storage capacity, we have proposed a method aimed at introducing the notion of memory into a class of widespread scheduling heuristics that exhibit both good performance and low complexity. Thanks to this technique, we achieved speedups over 20%.

The next step is to formalize an execution model on top of which a runtime software will be built. This implies specifying both the application requirements and modeling precisely the target platform, namely STHORM.

6.6. High-Performance Point-to-Point Communications

Participants: Alexandre Denis, Sébastien Barascou, Raymond Namyst.

- NEWMADELEINE is our communication library designed for high performance networks in clusters. We have worked on optimizations on low-level protocols so as to improve point-to-point performance.
- We have proposed a communication protocol [21] for InfiniBand that amortizes the cost of checksums as used by fault-tolerant MPI implementations. We have modeled the behavior of the network and proposed auto-tuning mechanisms to adapt the protocol to the hardware properties.
- This work was initiated in the context of the FP3C collaboration with the University of Tokyo.

FLOWERS Project-Team

6. New Results

6.1. Autonomous and Social Skill Learning and Development

6.1.1. Active Learning and Intrinsic Motivation

6.1.1.1. Active Learning of Inverse Models with Goal Babbling

Participants: Adrien Baranes, Pierre-Yves Oudeyer.

We have continued to elaborate and study our Self-Adaptive Goal Generation - Robust Intelligent Adaptive Curiosity (SAGG-RIAC) architecture as an intrinsically motivated goal exploration mechanism which allows active learning of inverse models in high-dimensional redundant robots. Based on active goal babbling, this allows a robot to efficiently and actively learn distributions of parameterized motor skills/policies that solve a corresponding distribution of parameterized tasks/goals. The architecture makes the robot sample actively novel parameterized tasks in the task space, based on a measure of competence progress, each of which triggers low-level goal-directed learning of the motor policy parameters that allow to solve it. For both learning and generalization, the system leverages regression techniques which allow to infer the motor policy parameters corresponding to a given novel parameterized task, and based on the previously learnt correspondences between policy and task parameters.
We have conducted experiments with high-dimensional continuous sensorimotor spaces in three different robotic setups: 1) learning the inverse kinematics in a highly-redundant robotic arm, 2) learning omnidirectional locomotion with motor primitives in a quadruped robot 1718 , 3) an arm learning to control a fishing rod with a flexible wire. We show that 1) exploration in the task space can be a lot faster than exploration in the actuator space for learning inverse models in redundant robots; 2) selecting goals maximizing competence progress creates developmental trajectories driving the robot to progressively focus on tasks of increasing complexity and is statistically significantly more efficient than selecting tasks randomly, as well as more efficient than different standard active motor babbling methods; 3) this architecture allows the robot to actively discover which parts of its task space it can learn to reach and which part it cannot.
This work was published in the journal Robotics and Autonomous Systems [22].

6.1.1.2. Exploration in Model-based Reinforcement Learning

Participants: Manuel Lopes, Tobias Lang, Marc Toussaint, Todd Hester, Peter Stone, Pierre-Yves Oudeyer.

Formal exploration approaches in model-based reinforcement learning estimate the accuracy of the currently learned model without consideration of the empirical prediction error. For example, PAC-MDP approaches such as R-MAX base their model certainty on the amount of collected data, while Bayesian approaches assume a prior over the transition dynamics. We propose extensions to such approaches which drive exploration solely based on empirical estimates of the learner's accuracy and learning progress. We provide a "sanity check" theoretical analysis, discussing the behavior of our extensions in the standard stationary finite state-action case. We then provide experimental studies demonstrating the robustness of these exploration measures in cases of non-stationary environments or where original approaches are misled by wrong domain assumptions. [46]. Furthermore, we studied how different exploration algorithms can be combine and selected at runtime. Typically the user must hand-tune exploration parameters for each different domain and/or algorithm that they are using. We introduced an algorithm called leo for learning to select among different exploration strategies on-line. This algorithm makes use of bandit-type algorithms to adaptively select exploration strategies based on the rewards received when following them. We show empirically that this method performs well across a set of five domains In contrast, for a given algorithm, no set of parameters is best across all domains. Our results demonstrate that the leo algorithm successfully learns the best exploration strategies on-line, increasing the received reward over static parameterizations of exploration and reducing the need for hand-tuning exploration parameters [42].

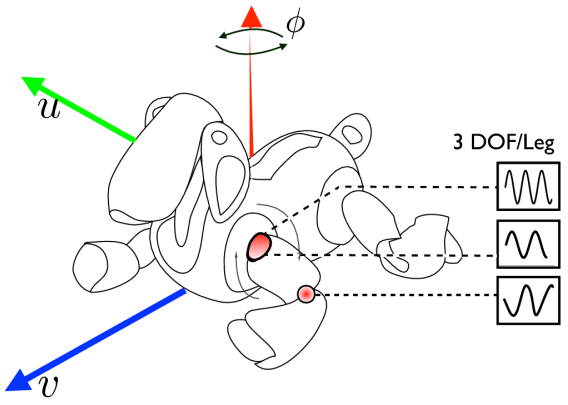


Figure 17. Experimenting SAGG-RIAC for learning an inverse model for omnidirectional locomotion of a quadruped robot. The quadruped robot is controlled using 24 dimensional motor synergies parameterized with 24 continuous values : 12 for the amplitudes and 12 others for the phases of a sinusoid tracked by each motor. Experiments consider a task space u, v, α which corresponds to the 2D position and orientation of the quadruped.

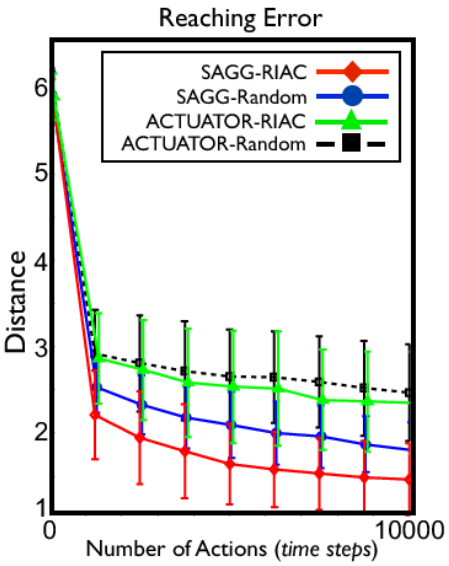
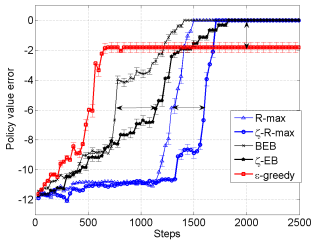
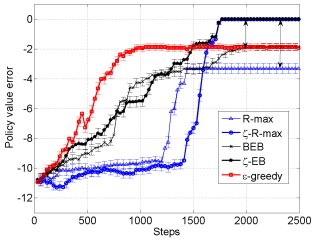


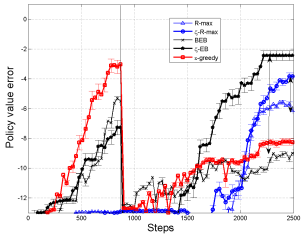
Figure 18. Evolution of the quality of the learnt inverse model for the quadruped robot experiment, depending on various exploration strategies (measured as mean error over a set of uniformly distributed goals generated independantly from learning trials).



(a) *Experiment 1—Correct Assumptions*



(b) *Experiment 2—Violated Assumptions*



(c) *Experiment 3—Change in Dynamics*

Figure 19. Experiments: (a) Like Rmax and BEB with correct assumptions, our algorithms ζ-Rmax and ζ-EB based on an empirical estimation of the learning progress converge to the optimal policy without relying on these assumptions, but take a small extra amount of time. (b) When their assumptions are violated, Rmax and BEB fail to converge, while ζ-Rmax and ζ-EB don't rely on these assumptions and again find the optimal policy. (c) In contrast to existing methods, ζ-Rmax and ζ-EB can cope with the change in transition dynamics after 900 steps and refocus their exploration.

6.1.1.3. The Strategic Student Approach for Life-Long Exploration and Learning

Participants: Manuel LOPES, Pierre-Yves OUDEYER.

We introduced and formalized a general class of learning problems for which a developmental learning strategy is shown to be optimal. This class of problems can be explained using the strategic student metaphor: a student has to learn a number of topics (or tasks) to maximize its mean score, and has to choose strategically how to allocate its time among the topics and/or which learning method to use for a given topic. We show that if the performance curves are sub-modular, then a strategy where time allocation or learning method are chosen in a developmental manner is optimal. We argue that this optimal developmental trajectory can be automatically generated by greedy maximization of learning progress. This optimal strategy amounts to creating a structured developmental exploration where typically easy tasks are first explored, and then progressively more complicated ones are explored. Furthermore, this result holds independently of the nature of the topics and the learning methods used. Then, we show an algorithm, based on multi-armed bandit techniques, that allows empirical online evaluation of learning progress and approximates the optimal solution. Finally, we show that the strategic student problem formulation allows to view in a common framework many previous approaches to active and developmental learning [47].

6.1.1.4. Active Inverse Reinforcement Learning through Generalized Binary Search

Participants: Manuel Lopes, Francisco Melo.

We contributed the first aggressive active learning algorithm for nonseparable multi-class classification. We generalize an existing active learning algorithm for binary classification [107] to the multi-class setting, and identify mild conditions under which the proposed method provably retains the main properties of the original algorithm, namely consistency and sample complexity. In particular, we show that, in the binary case, our method reduces to the original algorithm of [107]. We then contribute an extension of our method to multi-label settings, identify its main properties and discuss richer querying strategies. We conclude the paper with two illustrative application examples. The first application features a standard text-classification problem. The second application scenario features a learning from demonstration setting. In both cases we demonstrate the advantage of our active sampling approach against random sampling. We also discuss the performance of the proposed approach in terms of the derived theoretical bounds.

6.1.1.5. Towards high-dimensional and cumulative task space active exploration

Participant: Benureau Fabien.

One direction of research of the team has been on intrinsic motivation in the context of autonomous learning. Building on the PhD work of Adrien Baranes, the efforts have concentrated on creating algorithms capable to handle high-dimensional spaces and manage context with multiple tasks. The goal is for the learner to be able to autonomously create collection of reusable skills. In this context, two main research efforts have been led this year.

A typical robot is made of chains of joints. We can take advantage of the fact that joints earlier in the chain have more impact that joints further down. Given sensory feedback on the middle of the chain, an algorithm can use this information to boost learning speed and divide the learning space in subsets of smaller dimensions. We wanted to adapt this idea to high dimensional space, and specifically to the interaction with objects; a robotic arm that has already learned an inverse model of its kinematic could reuse this knowledge learn about the mapping between the position of the end-effector and the displacement of an object it is manipulating. Experiments were conducted, but they lead to the conclusion that such an approach, while effective in some specific setting, relies too heavily on a good representation of the end effector position and motion, which, in some cases, requires sensory space of higher dimension that the motor space, thus defeating the purpose. This approach was not found to be robust enough for the type of robotic context our lab is pursuing.

The SAGG-RIAC architecture is an efficient but complex architecture which implementation cannot be easily summarized in a few lines of pseudo-code. This is problematic because it reduces the ability of other research groups to implement and reuse our algorithms for their own work. An effort was started this year to create an implementation of SAGG-RIAC that would be more robust and simpler. The main idea was to use kernels rather than bins to estimate in interest in SAGG-RIAC. This approach led to very promising results, notably in

its ability to handle unbounded sensory spaces. We aim at publishing the result of this work in 2013, together with a publicly available implementation of our algorithms with easy to run examples for dissemination of active learning architectures elaborated in the team. This work will also be reused in the participation of the lab into the MaCSi project.

6.1.2. Learning and optimization of motor policies

6.1.2.1. Off-Policy Actor-Critic

Participants: Thomas Degris, Martha White, Richard Sutton.

Actor–critic architectures are an interesting candidate for learning with robots: they can represent complex stochastic policies suitable for robots, they can learn online and incrementally and their per-time-step complexity scales linearly with the number of learned weights. Moreover, interesting connections have been identified in the existing literature with neuroscience. Until recently, however, practical actor–critic methods have been restricted to the on-policy setting, in which the agent learns only about the policy it is executing.

In an off-policy setting, on the other hand, an agent learns about a policy or policies different from the one it is executing. Off-policy methods have a wider range of applications and learning possibilities. Unlike on-policy methods, off-policy methods are able to, for example, learn about an optimal policy while executing an exploratory policy, learn from demonstration, and learn multiple tasks in parallel from a single sensory-motor interaction with an environment. Because of this generality, off-policy methods are of great interest in many application domains.

We have presented the first actor-critic algorithm for off-policy reinforcement learning. Our algorithm is online and incremental, and its per-time-step complexity scales linearly with the number of learned weights. We have derived an incremental, linear time and space complexity algorithm that includes eligibility traces and empirically show better or comparable performance to existing algorithms on standard reinforcement-learning benchmark problems. This work was presented by Degris et al. [38] and was reproduced independently by Saminda Abeyruwan from the University of Miami.

6.1.2.2. Auto-Actor Critic

Participant: Thomas Degris.

As mentioned above, actor–critic architectures are an interesting candidate for robots to learn new skills in unknown and changing environments. However, existing actor–critic architectures, as many machine learning algorithms, require manual tuning of different parameters to work in the real world. To be able to systematize and scale-up skill learning on a robot, learning algorithms need to be robust to their parameters. The Flowers team has been working on making existing actor–critic algorithms more robust to make them suitable to a robotic setting. Results on standard reinforcement learning benchmarks are encouraging. This work will be submitted to international conference related with reinforcement learning. Interestingly, the methods developed in this work also offer a new formalism to think about different existing themes of Flowers research such as curiosity and maturational constraints.

6.1.2.3. Relationship between Black-Box Optimization and Reinforcement Learning

Participant: Freek Stulp.

Policy improvement methods seek to optimize the parameters of a policy with respect to a utility function. There are two main approaches to performing this optimization: reinforcement learning (RL) and black-box optimization (BBO). In recent years, benchmark comparisons between RL and BBO have been made, and there has been several attempts to specify which approach works best for which types of problem classes.

We have made several contributions to this line of research by: 1) Defining four algorithmic properties that further clarify the relationship between RL and BBO. 2) Showing how the derivation of ever more powerful RL algorithms displays a trend towards BBO. 3) Continuing this trend by applying two modifications to the state-of-the-art PI^2 algorithm, which yields an algorithm we denote PI^{BB}. We show that PI^{BB} is a BBO algorithm, and, more specifically, that it is a special case of the state-of-the-art CMAES algorithm. 4) Demonstrating that the simpler PI^{BB} achieves similar or better performance than PI^2 on several evaluation tasks. 5) Analyzing why BBO outperforms RL on these tasks. These contributions have been published on HAL [69], and have been submitted to JMLR.

This work has also resulted in the novel PI^2-CMA, PI^2-CMAES algorithms, which are presented in [63], [60], [62]

6.1.2.4. Reinforcement Learning with Sequences of Motion Primitives for Robust Manipulation

Participant: Freek Stulp.

Physical contact events often allow a natural decomposition of manipulation tasks into action phases and subgoals. Within the motion primitive paradigm, each action phase corresponds to a motion primitive, and the subgoals correspond to the goal parameters of these primitives. Current state-of-the-art reinforcement learning algorithms are able to efficiently and robustly optimize the parameters of motion primitives in very high-dimensional problems. These algorithms often consider only shape parameters, which determine the trajectory between the start- and end-point of the movement. In manipulation, however, it is also crucial to optimize the goal parameters, which represent the subgoals between the motion primitives. We therefore extend the policy improvement with path integrals (PI^2) algorithm to simultaneously optimize shape and goal parameters. Applying simultaneous shape and goal learning to sequences of motion primitives leads to the novel algorithm PI^2-Seq. We use our methods to address a fundamental challenge in manipulation: improving the robustness of everyday pick-and-place tasks. This work was published in IEEE Transactions on Robotics [31] and Robotics and Autonomous Systems [26].

6.1.2.5. Model-free Reinforcement Learning of Impedance Control in Stochastic Environments

Participant: Freek Stulp.

For humans and robots, variable impedance control is an essential component for ensuring robust and safe physical interaction with the environment. Humans learn to adapt their impedance to specific tasks and environments; a capability which we continually develop and improve until we are well into our twenties. We have reproduced functionally interesting aspects of learning impedance control in humans on a simulated robot platform.

As demonstrated in numerous force field tasks, humans combine two strategies to adapt their impedance to perturbations, thereby minimizing position error and energy consumption: 1) if perturbations are unpredictable, subjects increase their impedance through co-contraction; 2) if perturbations are predictable, subjects learn a feed-forward command to offset the perturbation. We show how a 7-DOF simulated robot demonstrates similar behavior with our model-free reinforcement learning algorithm , by applying deterministic and stochastic force fields to the robot's end-effector. We show the qualitative similarity between the robot and human movements.

Our results provide a biologically plausible approach to learning appropriate impedances purely from experience, without requiring a model of either body or environment dynamics. Not requiring models also facilitates autonomous development for robots, as pre-specified models cannot be provided for each environment a robot might encounter. This work was published in IEEE Transactions on Autonomous Mental Development [29].

6.1.2.6. Probabilistic optimal control: a quasimetric approach

Participants: Clément Moulin-Frier, Jacques Droulez, Steve Nguyen.

During his previous post-doc at the Laboratoire de Physiologie de la Perception et de l'Action (Collège de France, Paris), Clément Moulin-Frier joined Jacques Droulez and Steve N'Guyen to work on an alternative and original approach of probabilistic optimal control called the quasimetric. A journal paper (soon to be submitted) was written in 2012, where the authors propose a new approach for dealing with control under uncertainty.

6.1.3. Social learning and intrinsic motivation

6.1.3.1. Optimal Teaching on Sequential Decision Tasks

Participants: Manuel Lopes, Maya Cakmak.

A helpful teacher can significantly improve the learning rate of an autonomous learning agent. Teaching algorithms have been formally studied within the field of Algorithmic Teaching. These give important insights into how a teacher can select the most informative examples while teaching a new concept. However the field has so far focused purely on classification tasks. We introduced a novel method for optimally teaching sequential decision tasks. We present an algorithm that automatically selects the set of most informative demonstrations and evaluate it on several navigation tasks. Next, we present a set of human subject studies that investigate the optimality of human teaching in these tasks. We evaluate examples naturally chosen by human teachers and found that humans are generally sub-optimal. Then based on our proposed optimal teaching algorithm we try to elicit better teaching from humans. We do this by explaining the intuition of the teaching algorithm in an informal language prior to the teaching task. We found that this improves the examples elicited from human teachers on all considered tasks. This shows that a simple modification the instructions given to human teachers, has the potential of greatly improving the performance of the agent trained by the human [32].

6.1.3.2. Socially Guided Intrinsic Motivation for Skill Learning

Participants: Sao Mai Nguyen, Pierre-Yves Oudeyer.

We have explored how social interaction can bootstrap the learning of a robot for motor learning. We first studied how simple demonstrations by teachers could have a bootstrapping effect on autonomous exploration with intrinsic motivation by building a learner who uses both imitation learning and SAGG-RIAC algorithm [22], and thus designed the SGIM-D (Socially Guided Intrinsic Motivation by Demonstration) algorithm [105]. We then investigated on the reasons of this bootstrapping effect [55], to show that demonstrations by teachers can both enhance more tasks to be explored, as well as favor more easily generalized actions to be used. This analysis is generalizable for all algorithms using social guidance and goal-oriented exploration. We then proposed to build a strategic learner who can learn multiple tasks and with multiple strategies. An overview and theoretical study of multi-task, multi-strategy Strategic Learning is presented in [47]. We also forsook to build a learning algorithm for more natural interaction with the human users. We first designed the SGIM-IM algorithm so that it can determine itself when it should ask for help from the teacher while trying to explore autonomously as long as possible so as to use as little of the teacher's time as possible [54]. After tackling with the problem of how and when to learn, we also investigated an active learner who can determine who to ask for help: in the case of two teachers available, SGIM-IM can determine which strategy to adopt between autonomous exploration and learning by demonstration, and which teacher enhances most learning progress for the learner [56], and ask him for help.

While the above results have been shown in simulation environments: of a simple deterministic air hockey game (fig. 20), and a stochastic fishing experiment with a real-time physical simulator (fig. 21), we are now building the experimental setup of the fishing experiment in order to carry out the experiments with naive users.

6.1.3.3. Adaptive task execution for implicit human-robot coordination

Participants: Ievgen Perederieiev, Manuel Lopes, Freek Stulp.

We began a project which goal is to study how computational models of multi-agent systems can be applied in situations where one agent is a human. We aim at applications where robots collaborate with humans for achieving complex tasks..

A very important capability for efficient collaborative work is the mutual agreement of a task and the ability to predict the behavior of others. We address such aspect by studying methods that increase the predictability of the robot actions. An efficient motor execution becomes the one that not just optimize speed and minimizes energy but also the one that improves the reliability of the team behavior. We are studying policy gradient methods and working on policy improvement algorithms (PI^2, CEM and $CMAES$). A feasibility study will consider a simple task between a robot and a person where the goal is to coordinate the way a set of three colored buttons is pressed.

6.1.3.4. Formalizing Imitation Learning

Participants: Thomas Cederborg, Pierre-Yves Oudeyer.

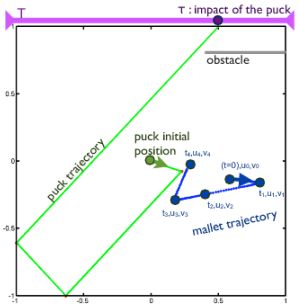


Figure 20. Illustration of SGIM-D and SGIM-IM algorithms

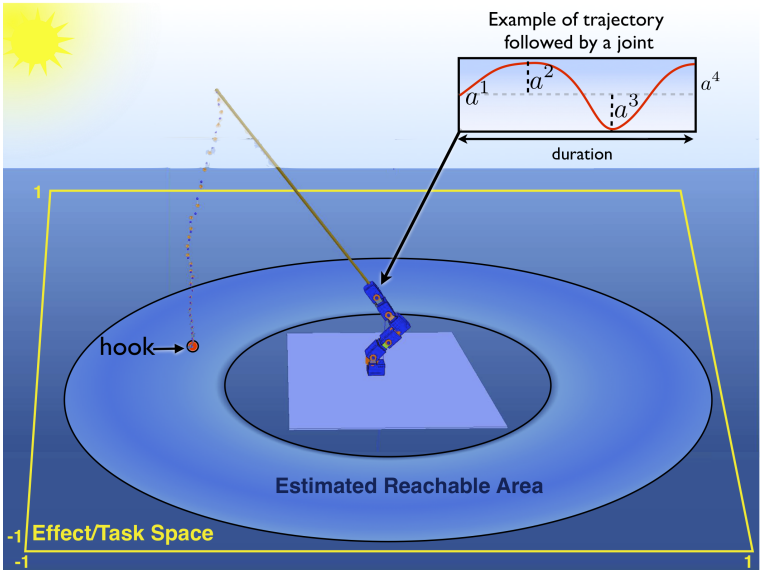


Figure 21. Illustration of SGIM-D and SGIM-IM algorithms

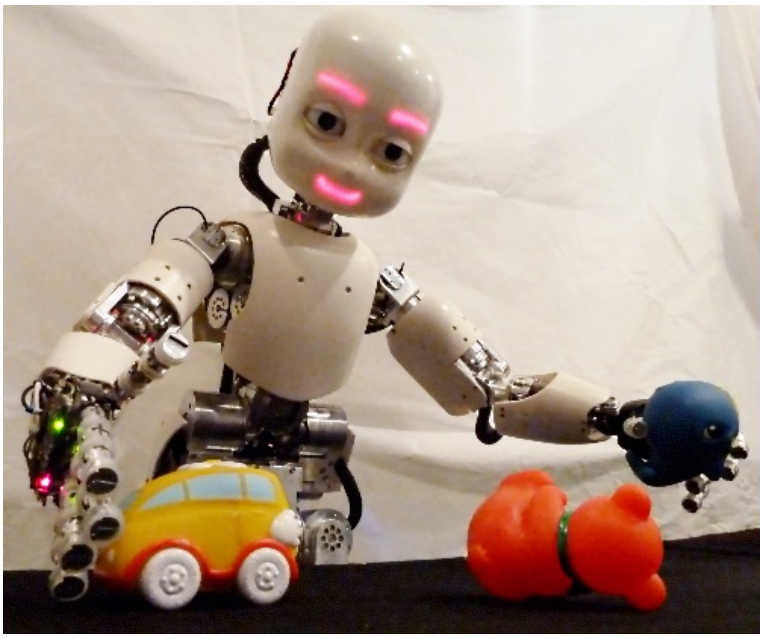


Figure 22. Illustration of SGIM-D and SGIM-IM algorithms

An original formalization of imitation learning was elaborated. Previous attempts to systematize imitation learning has been limited to categorizing different types of demonstrator goals (for example defining success in terms of the sequential joint positions of a dance, or in terms of environmental end states), and/or been limited to a smaller subset of imitation (such as learning from tele-operated demonstrations). The formalism proposed attempts to describe a large number of different types of learning algorithms using the same notation. Any type of algorithm that modifies a policy based on observations of a human, is treated as an interpretation hypothesis of this behavior. One example would be an update algorithm that updates a policy, partially based on the hypothesis that the demonstrator succeeds at demonstrations with probability 0.8, or an update algorithm that assumes that a scalar value is an accurate evaluation of an action compared to the latest seven actions. The formalism aims to give a principled way of updating these hypotheses, either rejecting some of a set of hypotheses regarding the same type of behavior, or set of parameters of an hypothesis. Any learning algorithm that modifies policy based on observations of a human that wants an agent to do something or act in some way, is describable as an interpretation hypothesis. If the learning algorithm is static, this simply corresponds to an hypothesis that is not updated based on observations. A journal article is currently being written.

6.1.4. Unsupervised learning of motor primitives

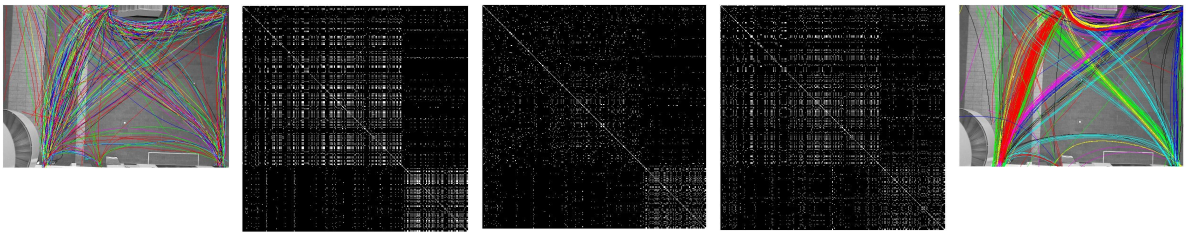
6.1.4.1. Clustering activities

Participants: Manuel Lopes, Luis Montesano.

Learning behaviors from data has applications in surveillance and monitoring systems, virtual agents and robotics among others. In our approach, ww assume that in a given unlabeled dataset of multiple behaviors, it is possible to find a latent representation in a controller space that allows to generate the different behaviors. Therefore, a natural way to group these behaviors is to search a common control system that generate them accurately.

Clustering behaviors in a latent controller space has two major challenges. First, it is necessary to select the control space that generate behaviors. This space will be parameterized by a set of features that will change for different behaviors. Usually, each controller will minimize a cost function with respect to several task features. The latent representation is in turn defined by the selected features and their corresponding weight. Second, an unknown number of such controllers is required to generate different behaviors and the grouping must be based on the ability of the controller to generate the demonstrations using a compact set of controllers.

We propose a Dirichlet Process based algorithm to cluster behaviors in a latent controller space which encodes the dynamical system generating the observed trajectories. The controller uses a potential function generated as a linear combination of features. To enforce sparsity and automatically select features for each cluster independently, we impose a conditional Laplace prior over the controller parameters. Based on this models, we derive a sparse Dirichlet Process Mixture Model (DPMM) algorithm that estimates the number of behaviors and a sparse latent controller for each of them based on a large set of features.



(a) (b) (c) (d) (e)

Figure 23. EIFPD dataset. (a) Trajectories of the EIFPD to be clustered (color is non-informative). (b-d) correspondence matrix for the 474 trajectories for the labeled ground truth, the KMeans in measurement space and the DPMM, respectively. (e) Reconstructed trajectories from the initial point using the estimated parameters of the DPMM algorithm. Due to the large number of clusters (37), colors are repeated for different clusters.

6.1.4.2. Learning the Combinatorial Structure of Demonstrated Behaviors with Inverse Feedback Control

Participants: Olivier Mangin, Pierre-Yves Oudeyer.

We have elaborated and illustrated a novel approach to learning motor skills from demonstration. This approach combines ideas from inverse feedback learning, in which actions are assumed to solve a task, and dictionary learning. In this work we introduced a new algorithm that is able to learn behaviors by assuming that the observed complex motions can be represented in a smaller dictionary of concurrent tasks. We developed an optimization formalism and show how we can learn simultaneously the dictionary and the mixture coefficients that represent each demonstration. We presented results on a idealized model where a set of potential functions represents human objectives or preferences for achieving a task in [51].

6.1.5. Maturational learning

6.1.5.1. Emergent Proximo-Distal Maturation through Adaptive Exploration

Participants: Freek Stulp, Pierre-Yves Oudeyer.

Life-long robot learning in the high-dimensional real world requires guided and structured exploration mechanisms. In this developmental context, we have investigated the use of the PI^2-CMAES episodic reinforcement learning algorithm, which is able to learn high-dimensional motor tasks through adaptive control of exploration. By studying PI^2-CMAES in a reaching task on a simulated arm, we observe two developmental properties. First, we show how PI^2-CMAES autonomously and continuously tunes the global exploration/exploitation trade-off, allowing it to re-adapt to changing tasks. Second, we show how PI^2-CMAES spontaneously self-organizes a maturational structure whilst exploring the degrees-of-freedom

(DOFs) of the motor space. In particular, it automatically demonstrates the so-called *proximo-distal maturation* observed in humans: after first freezing distal DOFs while exploring predominantly the most proximal DOF, it progressively frees exploration in DOFs along the proximo-distal body axis. These emergent properties suggest the use of PI^2-CMAES as a general tool for studying reinforcement learning of skills in life-long developmental learning contexts. This work was published in the IEEE International Conference on Developement and Learning [60].

6.1.5.2. Interaction of Maturation and Intrinsic Motivation for Developmental Learning of Motor Skills in Robots

Participants: Adrien Baranes, Pierre-Yves Oudeyer.

We have introduced an algorithmic architecture that couples adaptively models of intrinsic motivation and physiological maturation for autonomous robot learning of new motor skills. Intrinsic motivation, also called curiosity-driven learning, is a mechanism for driving exploration in active learning. Maturation denotes here mechanisms that control the evolution of certain properties of the body during development, such as the number and the spatio-temporal resolution of available sensorimotor channels. We argue that it is useful to introduce and conceptualize complex bidirectional interactions among these two mechanisms, allowing to actively control the growth of complexity in motor development in order to guide efficiently exploration and learning. We introduced a model of maturational processes, taking some functional inspiration from the myelination process in humans, and show how it can be coupled in an original and adaptive manner with the intrinsic motivation architecture SAGG-RIAC (Self-Adaptive Goal Generation - Robust Intelligent Adaptive Curiosity algorithm), creating a new system, called McSAGG-RIAC. We then conducted experiments to evaluate both qualitative and quantitative properties of these systems when applied to learning to control a high-dimensional robotic arm, as well as to learning omnidirectional locomotion in a quadruped robot equipped with motor synergies. We showed that the combination of active and maturational learning can allow to gain orders of magnitude in learning speed as well as reach better generalization performances. A journal article is currently being written.

6.1.6. Morphological computation and body intelligence

6.1.6.1. Comparative Study of the Role of Trunk in Human and Robot Balance Control

Participants: Matthieu Lapeyre [correspondant], Christophe Halgand, Jean-René Cazalet, Etienne Guillaud, Pierre-Yves Oudeyer.

Numerous studies in the field of functional motor rehabilitation were devoted to understanding the functioning of members but few are interested in the coordination of the trunk muscles and the relationship between axial and appendicular motricity which is essential in maintaining balance during travel. Acquiring new knowledge on this subject is a prerequisite in the development of new therapeutic strategies to restore motor function to the overall development of robotic orthosis that would assist the movement. Many robotic orthosis using EMG signals were unfortunately using few joints [85] and a system for controlling a multi articulated spine has not yet been developed. We propose here to use a multidisciplinary approach to define the neuro-mechanical principles where an axial system is operating in synergy with human and robot limbs.

To bring us a theoretical framework, we chose to study the reactions of the Acroban humanoid robot. Including 5 joints in the trunk, Acroban can reproduce in part the fluid movements of the human body [98] and especially to test its behavior when its trunk is held fixed or his arms are no longer used for rebalance. To disrupt postural balance in humans and robots, we have developed a low cost mobile platform (see Figure 24). This platform is made up of a broad stable support $(0.8x5m)$ mounted on a skateboard having a power of 800W. The substitution of the initial order of skate by an embedded microcontroller allows us to generate mono-axial perturbations precise intensity and duration to ensure repeatability of the disturbance. We capture movements (Optitrack 250Hz) and record the acceleration of the platform (accelerometer embedded 2kHz), the center of pressure (WiiBalanceBoard 60Hz), and electromyography (EMG).

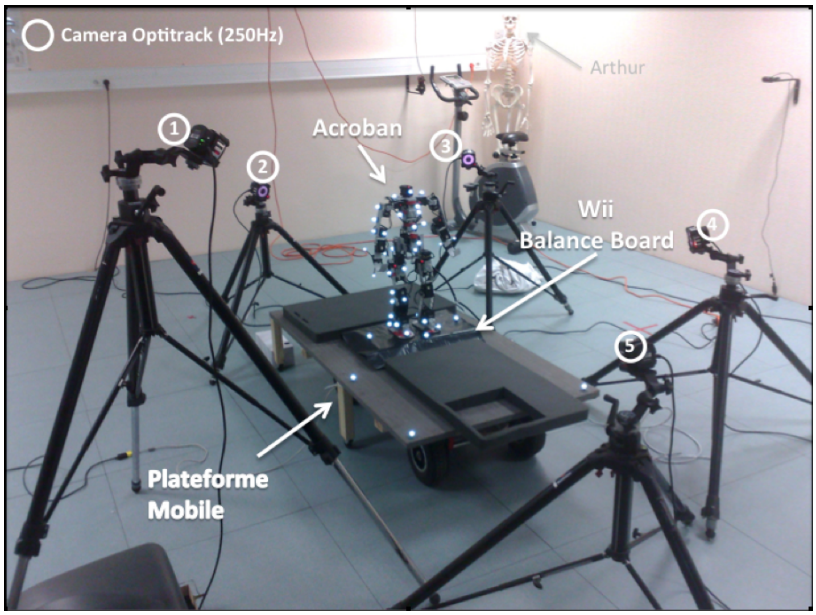


Figure 24. Experimental setup for comparative study of the role of the trunk in human and robot balance control

The experimental device (mobile platform and synchronized recordings) is operational. Preliminary experiments have allowed us to refine the profiles of disturbance on the robot Acroban. The analysis of preliminary results is in progress. Following this study, we hope to improve the modeling of the motor system in humans and robotic simulation as a basis for the development of robotic orthosis axial system. Second, the results provide a basis for improved balancing of Acroban primitives but also the development of future humanoid robots.

6.2. Autonomous and Social Perceptual Learning

6.2.1. The Impact of Human-Robot Interfaces on the Learning of Visual Objects

Participants: Pierre Rouanet, Pierre-Yves Oudeyer, Fabien Danieau, David Filliat.

We have continued and finalized a large-scale study of the impact of interfaces allowing non-expert users to efficiently and intuitively teach a robot to recognize new visual objects. We identified challenges that need to be addressed for real-world deployment of robots capable of learning new visual objects in interaction with everyday users. We argue that in addition to robust machine learning and computer vision methods, well-designed interfaces are crucial for learning efficiency. In particular, we argue that interfaces can be key in helping non-expert users to collect good learning examples and thus improve the performance of the overall learning system. Then, we have designed four alternative human-robot interfaces: three are based on the use of a mediating artifact (smartphone, wiimote, wiimote and laser), and one is based on natural human gestures (with a Wizard-of-Oz recognition system). These interfaces mainly vary in the kind of feedback provided to the user, allowing him to understand more or less easily what the robot is perceiving, and thus guide his way of providing training examples differently. We then evaluated the impact of these interfaces, in terms of learning efficiency, usability and user's experience, through a real world and large scale user study. In this experiment, we asked participants to teach a robot twelve different new visual objects in the context of a robotic game. This game happens in a home-like environment and was designed to motivate and engage users in an interaction where using the system was meaningful. We then analyzed results that show significant differences among

interfaces. In particular, we showed that interfaces such as the smartphone interface allows non-expert users to intuitively provide much better training examples to the robot, almost as good as expert users who are trained for this task and aware of the different visual perception and machine learning issues. We also showed that artifact-mediated teaching is significantly more efficient for robot learning, and equally good in terms of usability and user's experience, than teaching thanks to a gesture-based human-like interaction.
This work was accepted for publication in the IEEE Transactions on Robotics [28].


(a) draw the attention toward an object (b) trigger the capture (c) encircle the area of the object (d) the new learning example

Figure 25. Smartphone Interface. To make the robot collect a new learning example, users have to first draw the robot's attention toward the object they want to teach through simple gestures. Once the robot sees the object, they touch the head of the robot to trigger the capture. Then, they directly encircle the area of the image that represents the object on the screen. The selected area is then used as the new learning example. The combination of the video stream and the gestures facilitate the achievement of joint attention.

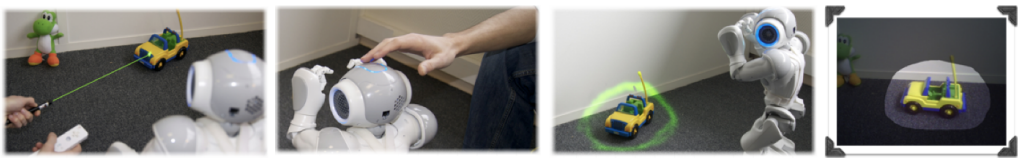

(a) draw the attention toward an object (b) trigger the capture (c) encircle the area of the object (d) the new learning example

Figure 26. Wiimote + laser pointer interface. With this interface users can draw the robot's attention with a laser pointer toward an object. The laser spot is automatically tracked by the robot. They can ensure that the robot detects the spot thanks to haptic feedback on the Wiimote. Then, they can touch the head of the robot to trigger the capture of a new learning example. Finally, they encircle the object with the laser pointer to delimit its area which will be defined as the new learning example.

6.2.2. Curiosity-driven exploration and interactive learning of visual objects with the ICub robot

Participants: Mai Nguyen, Serena Ivaldi, Natalia Lyubova, Alain Droniou, Damien Gerardeaux-Viret, David Filliat, Vincent Padois, Olivier Sigaud, Pierre-Yves Oudeyer.

We studied how various mechanisms for cognition and learning, such as curiosity, action selection, imitation, visual learning and interaction monitoring, can be integrated in a single embodied cognitive architecture. We have conducted an experiment with the iCub robot for active recognition of objects in 3D through curiosity-driven exploration, in which the robot can manipulate the robot or ask a human user to manipulate objects to gain information and recognise better objects (fig. 22). For this experiment carried out within the MACSi project, we address the problem of learning to recognise objects in a developmental robotics scenario. In a life-long learning perspective, a humanoid robot should be capable of improving its knowledge of objects

Figure 27. The real world environment designed to reproduce a typical living room. Many objects were added in the scene in order to make the environment cluttered.

with active perception. Our approach stems from the cognitive development of infants, exploiting active curiosity-driven manipulation to improve perceptual learning of objects. These functionalities are implemented as perception, control and active exploration modules as part of the Cognitive Architecture of the MACSi project. We integrated a bottom-up vision system based on swift feature points and motor-primitive based robot control with the SGIM-ACTS algorithm (Socially Guided Intrinsic Motivation with Active Choice of Task and Strategy as the active exploration module. SGIM-ACTS is a strategic learner who actively chooses which task to concentrate on, and which strategy is better according to this task. It thus monitors the learning progress for each strategy on all kinds of tasks, and actively interacts with the human teacher. We obtained an active object recognition approach, which exploits curiosity to guide exploration and manipulation, such that the robot can improve its knowledge of objects in an autonomous and efficient way. Experimental results show the effectiveness of our approach: the humanoid iCub is now capable of deciding autonomously which actions must be performed on objects in order to improve its knowledge, requiring a minimal assistance from its caregiver. This work constitutes the base for forthcoming research in autonomous learning of affordances.

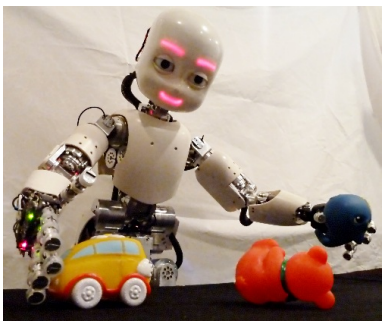


Figure 28. iCub performing curiosity-driven exploration and active recognition of visual objects in 3D

6.2.3. Discovering object concept through developmental learning

Participants: Natalia Lyubova, David Filliat.

The goal of this work is to design a visual system for a humanoid robot. Taking inspiration from child perception and following the principles of developmental robotics, the robot should detect and learn objects from interactions with people and from experiments it performs with objects, avoiding the use of image databases or of a separate training phase. In our model, all knowledge is therefore iteratively acquired from low-level features and builds up hierarchical object models, which are robust to changes in the environment, background and camera motion. In our scenario, people in front of the robot are supposed to interact with objects to encourage the robot to focus on them. We therefore assume that the robot is attracted by motion and we segment possible objects based on clustering of the optical flow. Additionally, the depth information from a Kinect is used to filter visual input, considering the constraints of the robot's working area and to refine the object contours obtained from motion segmentation.

The appearance of objects is encoded following the Bag of Visual Words approach with incremental dictionaries. We combine several complementary features to maximize the completeness of the encoded information (SURF descriptor and superpixels with associated colors) and construct pairs and triples of these features to integrate local geometry information. These features make it possible to decide if the current view has been already seen or not. A multi-view object model is then constructed by associating recognized views and views tracked during manipulations with an object.

This system is implemented on the iCub humanoid robot, which detects objects in the visual space and characterizes their appearance, their relative position and their occurrence statistics. The experiments were performed with up to ten objects; each of them was manipulated by a person during 1-2 minutes. Once the vocabulary reached a sufficient amount of knowledge, the robot was able to reliably recognize most of objects [48], [49], [43].

6.2.4. Unsupervised object categorization

Participants: Natalia Lyubova, David Filliat.

The developed unsupervised algorithm allows to identify segmented units of attention based on motion and depth information (proto-objects) into different categories such as robot hands, objects and humans.

The robot self-body category is discovered from the correlation between the proto-object positions and proprioception on the robot arms. This correlation it estimated by computing the mutual information between the changes in robot motor joints and the motion behavior of proto-objets in the visual field. The arm joints states are recorded from the robot and quantized to a vocabulary of possible arm configurations. The visual space is analyzed at the level of visual clusters that divide the perception field into regular regions. The mutual information is computed from the occurrence probabilities of the arm configurations and visual clusters.

In case of high correlation, the visual cluster is identified as a robot hand. Among the remaining proto-objects, objects are distinguished from human hands based on their quasi-static nature. Since most of objects don't move by themselves but rather are displaced by external forces, the object category is associated with regions of the visual space moving together mostly with recognized robot hands or human parts. This process make it possible to recognize the robot hands, even in case of changing appearance, and to learn to separate objects from parts of the caregivers bodies.

6.2.5. Efficient online bootstrapping of sensory representations

Participant: Alexander Gepperth.

This work [24] is a simulation-based investigation exploring a novel approach to the open-ended formation of multimodal representations in autonomous agents. In particular, we addressed here the issue of transferring (bootstrapping) features selectivities between two modalities, from a previously learned or innate reference representation to a new induced representation. We demonstrated the potential of this algorithm by several experiments with synthetic inputs modeled after a robotics scenario where multimodal object representations are bootstrapped from a (reference) representation of object affordances, focusing particularly on typical challenges in autonomous agents: absence of human supervision, changing environment statistics and limited computing power. We proposed an autonomous and local neural learning algorithm termed PROPRE (projection-prediction) that updates induced representations based on predictability: competitive advantages

are given to those feature-sensitive elements that are inferable from activities in the reference representation, the key ingredient being an efficient online measure of predictability controlling learning. We verified that the proposed method is computationally efficient and stable, and that the multimodal transfer of feature selectivity is successful and robust under resource constraints. Furthermore, we successfully demonstrated robustness to noisy reference representations, non-stationary input statistics and uninformative inputs.

6.2.6. Simultaneous concept formation driven by predictability

Participants: Alexander Gepperth, Louis-Charles Caron.

This work [40] was conducted in the context of developmental learning in embodied agents who have multiple data sources (sensors) at their disposal. We developed an online learning method that simultaneously discovers meaningful concepts in the associated processing streams, extending methods such as PCA, SOM or sparse coding to the multimodal case. In addition to the avoidance of redundancies in the concepts derived from single modalities, we claim that meaningful concepts are those who have statistical relations across modalities. This is a reasonable claim because measurements by different sensors often have common cause in the external world and therefore carry correlated information. To capture such cross-modal relations while avoiding redundancy of concepts, we propose a set of interacting self-organization processes which are modulated by local predictability. To validate the fundamental applicability of the method, we conducted a plausible simulation experiment with synthetic data and found that those concepts which are predictable from other modalities successively ”grow”, i.e., become overrepresented, whereas concepts that are not predictable become systematically under-represented. We additionally explored the applicability of the developed method to real-world robotics scenarios.

6.2.7. The contribution of context: a case study of object recognition in an intelligent car

Participants: Alexander Gepperth, Michael Garcia Ortiz.

In this work [23], we explored the potential contribution of multimodal context information to object detection in an ”intelligent car”. The used car platform incorporates subsystems for the detection of objects from local visual patterns, as well as for the estimation of global scene properties (sometimes denoted scene context or just context) such as the shape of the road area or the 3D position of the ground plane. Annotated data recorded on this platform is publicly available as the a ”HRI RoadTraffic” vehicle video dataset, which formed the basis for the investigation. In order to quantify the contribution of context information, we investigated whether it can be used to infer object identity with little or no reference to local patterns of visual appearance. Using a challenging vehicle detection task based on the ”HRI RoadTraffic” dataset, we trained selected algorithms (context models) to estimate object identity from context information alone. In the course of our performance evaluations, we also analyzed the effect of typical real-world conditions (noise, high input dimensionality, environmental variation) on context model performance. As a principal result, we showed that the learning of context models is feasible with all tested algorithms, and that object identity can be estimated from context information with similar accuracy as by relying on local pattern recognition methods. We also found that the use of basis function representations [1] (also known as ”population codes” allows the simplest (and therefore most efficient) learning methods to perform best in the benchmark, suggesting that the use of context is feasible even in systems operating under strong performance constraints.

6.2.8. Co-training of context models for real-time object detection

Participant: Alexander Gepperth.

In this work[41], we developed a simple way to reduce the amount of required training data in context-based models of real- time object detection and demonstrated the feasibility of our approach in a very challenging vehicle detection scenario comprising multiple weather, environment and light conditions such as rain, snow and darkness (night). The investigation is based on a real-time detection system effectively composed of two trainable components: an exhaustive multiscale object detector (signal-driven detection), as well as a module for generating object-specific visual attention (context models) controlling the signal-driven detection process. Both parts of the system require a significant amount of ground-truth data which need to be generated by

human annotation in a time-consuming and costly process. Assuming sufficient training examples for signal-based detection, we showed that a co-training step can eliminate the need for separate ground-truth data to train context models. This is achieved by directly training context models with the results of signal-driven detection. We demonstrated that this process is feasible for different qualities of signal-driven detection, and maintains the performance gains from context models. As it is by now widely accepted that signal-driven object detection can be significantly improved by context models, our method allows to train strongly improved detection systems without additional labor, and above all, cost.

6.3. Joint Learning and Development of Language and Action

6.3.1. Learning to recognize parallel motion primitives with linguistic descriptions using Non-Negative Matrix Factorization

Participants: Olivier Mangin, Pierre-Yves Oudeyer.

We have elaborated and experimented a novel approach to joint language and motor learning from demonstration. It enables discovery of a dictionary of gesture and linguistic primitives, that can be combined in parallel to represent training data as well as novel activities in the form of combinations of known gestures. These methods and the results of our experiments participate in addressing two main issues of developmental robotics: 1) symbol grounding for language learning; 2) achieving compositionality in motor-learning from demonstration, which enables re-using knowledge and thus scaling to complex tasks. In particular, we are interested in learning motor primitives active in parallel, a less explored way of combining such primitives. To address these challenges we have explored and studied the use of nonnegative matrix factorization to discover motor primitives from histogram representations of data acquired from real demonstrations of dancing movements. Initial results were presented in [99] and further results are presented in [52].

6.3.2. Curiosity-driven phonetic learning

Participants: Clément Moulin-Frier, Pierre-Yves Oudeyer.

We study how developmental phonetic learning can be guided by pure curiosity-driven exploration, also called intrinsically motivated exploration. Phonetic learning refers here to learning how to control a vocal tract to reach acoustic goals. We compare three different exploration strategies for learning the auditory-motor inverse model: random motor exploration, random goal selection with reaching, and curiosity-driven active goal selection with reaching. Using a realistic vocal tract model, we show how intrinsically motivated learning driven by competence progress can generate automatically developmental structure in both articulatory and auditory modalities, displaying patterns in line with some experimental data from infants. This work has been published in [53] and received the best paper award in computational models of development at the International Conference on Development and Learning, Epirob, San Diego, 2012.

We are now working on applying this approach to the control of a more complex articulatory synthesizer. We are interested in using the free software Praat, a powerful tool allowing to synthesize a speech signal from a trajectory in a 29-dimensional space of respiratory and oro-facial muscles. Numerous acoustic features can in turn be extracted from the synthesized sound, among which the Mel-frequency cepstral coefficients. Our hope is that a developmental robotics approach applied to a realistic articulatory model can appropriately manage the learning process of this complex mapping in high-dimensional spaces , and that observed developmental sequences can lead to interesting experimental data comparisons and predictions. In particular, using such a dynamic model controlled by muscle activity could hopefully allow to relate our results to more common speech acquisition data, in particular regarding infraphonological exploration and babbling.

6.3.3. Towards robots with teleological action and language understanding

Participants: Britta Wrede, Katharina Rohlfing, Jochen Steil, Sebastian Wrede, Jun Tani, Pierre-Yves Oudeyer.

It is generally agreed upon that in order to achieve generalizable learning capabilities of robots they need to be able to acquire compositional structures - whether in language or in action. However, in human development the capability to perceive compositional structure only evolves at a later stage. Before the capability to understand action and language in a structured, compositional way arises, infants learn in a holistic way which enables them to interact in a socially adequate way with their social and physical environment even with very limited understanding of the world, e.g. trying to take part in games without knowing the exact rules. This capability endows them with an action production advantage which elicits corrective feedback from a tutor, thus reducing the search space of possible action interpretations tremendously. In accordance with findings from developmental psychology we argue that this holistic way is in fact a teleological representation encoding a goal-directed perception of actions facilitated through communicational frames. This observation leads to a range of consequences which need to be verified and analysed in further research. We have written an article [64] where we discussed two hypotheses how this can be made accessible for action learning in robots: (1) We explored the idea that the teleological approach allows some kind of highly reduced one shot learning enabling the learner to perform a meaningful, although only partially correct action which can then be further refined through compositional approaches. (2) We discussed the possibility to transfer the concept of ”conversational frames” as recurring interaction patterns to the action domain, thus facilitating to understand the meaning of a new action. We conclude that these capabilities need to be combined with more analytical compositional learning methods in order to achieve human-like learning performance.

6.3.4. Imitation Learning and Language

Participants: Thomas Cederborg, Pierre-Yves Oudeyer.

We have studied how context-dependant imitation learning of new skills and language learning could be seen as special cases of the same mechanism. We argue that imitation learning of context-dependent skills implies complex inferences to solve what we call the ”motor Gavagai problem”, which can be viewed as a generalization of the so-called ”language Gavagai problem”. In a full symbolic framework where percepts and actions are continuous, this allows us to articulate that language may be acquired out of generic sensorimotor imitation learning mechanisms primarily dedicated at solving this motor Gavagai problem. Through the use of a computational model, we illustrate how non-linguistic and linguistic skills can be learnt concurrently, seamlessly, and without the need for symbols. We also show that there is no need to actually represent the distinction between linguistic and non-linguistic tasks, which rather appears to be in the eye of the observer of the system. This computational model leverages advanced statistical methods for imitation learning, where closed-loop motor policies are learnt from human demonstrations of behaviours that are dynamical responses to a multimodal context. A novelty here is that the multimodal context, which defines what motor policy to achieve, includes, in addition to physical objects, a human interactant which can produce acoustic waves (speech) or hand gestures (sign language). A book chapter was written and published [66] and a journal article was submitted.

6.3.5. COSMO (“Communicating about Objects using Sensory-Motor Operations”): a Bayesian modeling framework for studying speech communication and the emergence of phonological systems

Participants: Clément Moulin-Frier, Jean-Luc Schwartz, Julien Diard, Pierre Bessière.

This work began with the PhD thesis of Clement Moulin-Frier at GIPSA-Lab, Grenoble, France, supervised by Jean-Luc Schwartz (GIPSA-Lab, CNRS), Julien Diard (LPNC, CNRS) and Pierre Bessière (College de France, CNRS). A few papers were finalized during his post-doc at FLOWERS in 2012. Firstly, an international journal paper based on the PhD thesis work of Raphael Laurent (GIPSA-Lab), extending Moulin-Frier’s model, was published [25], and a commentary in *Behavioral and Brain Sciences* was accepted but not yet published [68]. Both these papers provide computational arguments based on a sensory-motor cognitive model to feed the age-old debate of motor vs. auditory theories of speech perception. Secondly, in another journal paper under the submission process, we attempt to derive some properties of phonological systems (the sound systems of human languages) from the mere properties of speech communication. We introduce a model of the cognitive

architecture of a communicating agent, called COSMO (for "Communicating about Objects using Sensory-Motor Operations") that allows expressing in a probabilistic way the main theoretical trends found in the speech production and perception literature. This allows a computational comparison of these theoretical trends, helping to identify the conditions that favor the emergence of linguistic codes. We present realistic simulations of phonological system emergence showing that COSMO is able to predict the main regularities in vowel, stop consonant and syllable systems in human languages.

6.3.6. Recognizing speech in a novel accent: the Motor Theory of Speech Perception reframed

Participants: Clément Moulin-Frier, Michael Arbib.

Clément Moulin-Frier engaged this work with Michael Arbib during his 6-month visit in 2009 at the USC Brain Project, University of Southern California, Los Angeles, USA. An international journal paper is still under the revision process, in which we offer a novel computational model of foreign-accented speech adaptation, together with a thorough analysis of its implications with respect to the motor theory of speech perception.

6.3.7. Learning Simultaneously New Tasks and Feedback Models in Socially Guided Robot Learning

Participants: Manuel Lopes, Jonathan Grizou, Thomas Cederborg, Pierre-Yves Oudeyer.

We have developed a system that allows a robot to learn simultaneously new tasks and feedback models from ambiguous feedback in the context of robot learning by imitation. We have considered an inverse reinforcement learner that receives feedback from a user with an unknown and noisy protocol. The system needs to estimate simultaneously what the task is, and how the user is providing the feedback. We have further explored the problem of ambiguous protocols by considering that the words used by the teacher have an unknown relation with the action and meaning expected by the robot. This allows the system to start with a set of known symbols and learn the meaning of new ones. We have conducted human-robot interaction experiments where the user teaches a robot new tasks using natural speech with words unknown to the robot. The robot needs to estimate simultaneously what the task is and the associated meaning of words pronounced by the user. We have computational results showing that: a) it is possible to learn the task under unknown and noisy feedback, b) it is possible to reuse the acquired knowledge for learning new tasks and c) even in the presence of a known feedback, the use of extra unknown feedback signals while learning improves learning efficiency and robustness to mistakes. This algorithm has been applied on discrete and continuous problems and tested in a real world experiment using spoken words as feedback signals. A article to be submitted to a journal is currently being written.

6.3.8. Active Learning for Teaching a Robot Grounded Relational Symbols

Participants: Johannes Kulick, Tobias Lang, Marc Toussaint, Manuel Lopes.

The present work investigates an interactive teaching scenario, where a human aims to teach the robot symbols that abstract geometric (relational) features of objects. There are multiple motivations for this scenario: First, state-of-the-art methods for relational Reinforcement Learning demonstrated that we can successfully learn abstracting and well-generalizing probabilistic relational models and use them for goal-directed object manipulation. However, these methods rely on given grounded action and state symbols and raise the classical question Where do the symbols come from? Second, existing research on learning from human-robot interaction has focused mostly on the motion level (e.g., imitation learning). However, if the goal of teaching is to enable the robot to autonomously solve sequential manipulation tasks in a goal-directed manner, the human should have the possibility to teach the relevant abstractions to describe the task and let the robot eventually leverage powerful relational RL methods (see Figure 29). We formalize human-robot teaching of grounded symbols as an Active Learning problem, where the robot actively generates geometric situations that maximize his information gain about the symbol to be learnt. We demonstrate that the learned symbols can be used in a relational RL framework for the robot to learn probabilistic relational rules and use them to solve object manipulation tasks in a goal-directed manner. [44].

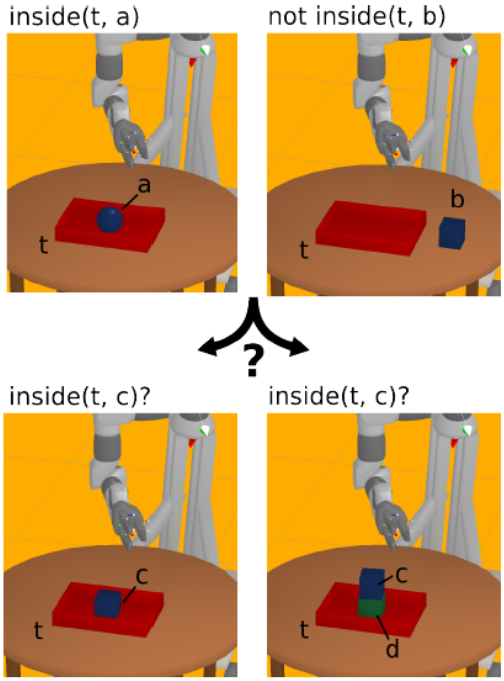


Figure 29. Active learning of symbol descriptions on a real world robot.

6.3.9. Multimodal Conversational Interaction with a Humanoid Robot

Participants: Adam Csapo, Emer Gilmartin, Jonathan Grizou, JingGuang Han, Raveesh Meena, Dimitra Anastasiou, Kristiina Jokinen, Graham Wilcock.

The paper presents a multimodal conversational interaction system for the Nao humanoid robot. The system was developed at the 8th International Summer Workshop on Multi-modal Interfaces, Metz, 2012. We implemented WikiTalk, an existing spoken dialog system for open-domain conversations, on Nao. This greatly extended the robot's interaction capabilities by enabling Nao to talk about an unlimited range of topics. In addition to speech interaction, we developed a wide range of multimodal interactive behaviours by the robot, including face- tracking, nodding, communicative gesturing, proximity detection and tactile interrupts. We made video recordings of user interactions and used questionnaires to evaluate the system. We further extended the robot's capabilities by linking Nao with Kinect. This work was presented in [34].

6.4. Other applications

6.4.1. Real-time Reaction-Diffusion Simulation: a Machine Learning Technique

Participants: Thomas Degris, Nejib Zemzemi.

Carmen is an Inria team working on modeling the electrical activity of the human heart. Their models are mainly based on reaction-diffusion equations. These methods are expansive in terms of computational costs which limits their use in practice. More specifically, some recent chirurgical intervention techniques on the heart (atrial ablation) requires to identify the source of the electrical wave. Finding such sources requires an optimization procedure. Using classical methods, this procedure is very heavy computationally.

In this project, our goal is to reduce the computational cost using supervised learning techniques. The idea is to replace the incremental resolution of partial differential equations by more suitable data structures for real-time running. Starting from data generated by simulating different excitations scenari on a human atria, this data is afterwords used as a training data set for machine learning algorithms. This approach will allow a faster optimization procedure.

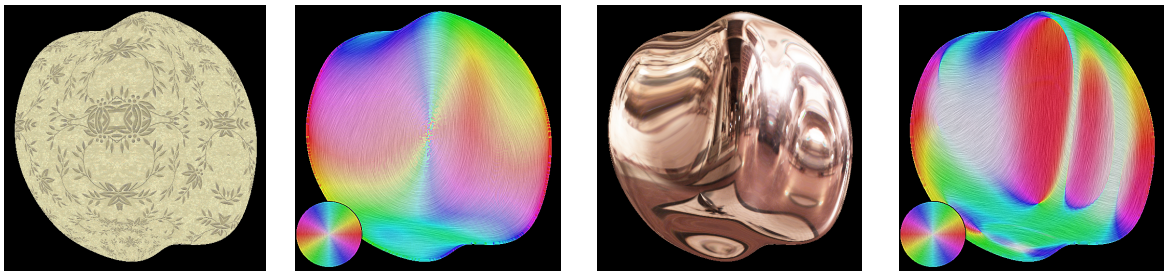
This work is in collaboration with Nejib Zemzemi from the Inria Carmen team. This project is in preliminary steps.

MANAO Team

5. New Results

5.1. Axis 1:Analysis and Simulation

5.1.1. First Order Analysis of Shading



Texuring | 1st order gradient field | Environment reflection | 2st order gradient field

Figure 8. First-oder analysis [21] have shown that shading variations are caused by depth variations (first-order gradient field) and by normal variations (second-order fields). These fields are visualized using hue and saturation to indicate direction and magnitude of the flow respectively.

We introduced [21] a novel method for producing convincing pictures of shaded objects based entirely on 2D image operations. This approach, which we call image-based shading design, offers direct artistic control in the picture plane by deforming image primitives so that they appear to conform to specific 3D shapes. Using a differential analysis of reflected radiance, we have identified the two types of surface flows involved in the depiction of shaded objects, which are consistent with recent perceptual studies. We have also introduced two novel deformation operators that closely mimic surface flows while providing direct artistic controls in real-time.

5.1.2. Rational BRDF

Over the last two decades, much effort has been devoted to accurately measuring Bidirectional Reflectance Distribution Functions (BRDFs) of real-world materials and to use efficiently the resulting data for rendering. Because of their large size, it is difficult to use directly measured BRDFs for real-time applications, and fitting the most sophisticated analytical BRDF models is still a complex task. In this paper, we introduce Rational BRDF [19], a general-purpose and efficient representation for arbitrary BRDFs, based on Rational Functions (RFs). Using an adapted parametrization, we demonstrate how Rational BRDFs offer 1) a more compact and efficient representation using low-degree RFs, 2) an accurate fitting of measured materials with guaranteed control of the residual error, and 3) efficient importance sampling by applying the same fitting process to determine the inverse of the Cumulative Distribution Function (CDF) generated from the BRDF for use in Monte-Carlo rendering.

5.2. Axis 2: From Acquisition to Display

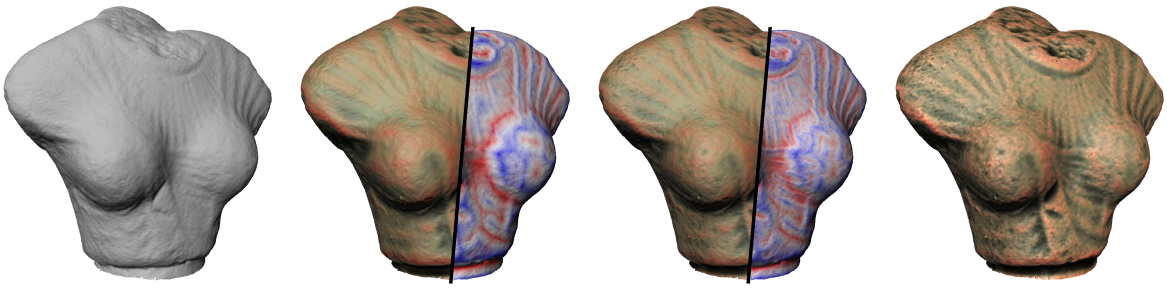
5.2.1. Outdoor Lighting for Augmented Reality

Figure 9. Consistent illumination of a virtual car in real outdoor lighting.

In augmented reality, one of the key tasks to achieve a convincing visual appearance consistency between virtual objects and video scenes is to have a coherent illumination along the whole sequence. As outdoor illumination is largely dependent on the weather, the lighting condition may change from frame to frame. We have proposed [17] a full image-based approach for online tracking of outdoor illumination variations from videos captured with moving cameras. Our key idea is to estimate the relative intensities of sunlight and skylight via a sparse set of planar feature-points extracted from each frame. To address the inevitable feature misalignments, a set of constraints are introduced to select the most reliable ones. Exploiting the spatial and temporal coherence of illumination, the relative intensities of sunlight and skylight are finally estimated by using an optimization process. We have validated our technique on a set of real-life videos and show that the results with our estimations are visually coherent along the video sequences (cf. Figure 9).

5.3. Axis 3: Rendering, Visualization and Illustration

5.3.1. Surface Relief Analysis for Illustrative Shading

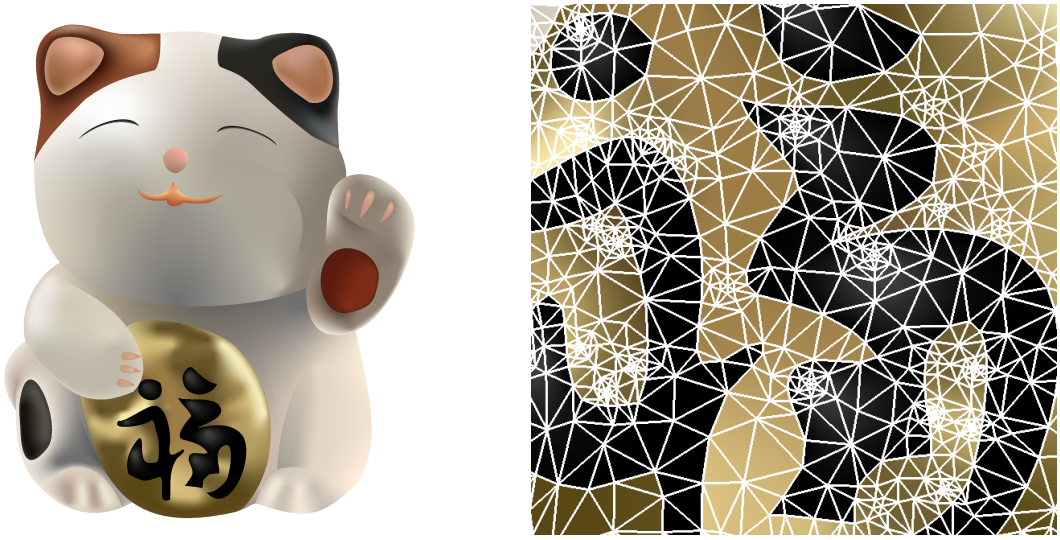


(a) (b) (c) (d)

Figure 10. Given a detailed surface (a), we analyze its relief to locate relief features in the neighborhood of each surface point (b). We focus on three types of features: convexities, concavities, and inflexions, shown on the right half with blue, red and white colors respectivelly. Extracted information is used to assign them different shading functions: here we use three different lit-spheres, shown on the left half. An additional accessibility shading effect helps convey relief cavities. Features are extracted and combined at multiple scales to depict relevant relief details (c). Finally, radiance scaling is added to enhance the relief based on the curvature at each feature (d).

Rendering techniques are often used to convey shape in scientific illustrations. We present an analysis technique that leverages the complexity found in detailed 3D models for illustrative shading purposes. Given a smooth base surface with relief, it locates relief features (concavities, convexities and inflections) around each surface point and at multiple scales, using cubic-polynomial fitting. This object-space, per-vertex information is then used to guide a variety of shading techniques including normal enhancement, feature visualization, accessibility shading and radiance scaling. Thanks to this approach, features at multiple scales are easily combined, filtered and shaded, allowing users to explore surface relief in real-time (cf. Figure 10).

5.4. Axis 4: Editing and Modeling



(a) (b)

Figure 11. A complex image obtained using our vectorial solver (a), with a close-up view showing the automatically generated intermediate triangle mesh (b).

5.4.1. Free form vector gradients

The creation of free-form vector drawings as been greatly improved in recent years with techniques based on harmonic or bi-harmonic interpolation. Such methods offer the best trade-off between sparsity (keeping the number of control points small) and expressivity (achieving complex shapes and gradients). Unfortunately, the lack of a robust and versatile method to compute such images still limits their use in real-world applications. We developed a vectorial solver for the computation of free-form vector gradients based on a non-conform Finite Element Methods (FEM). Its key feature is to output a low-level vector representation suitable for very fast GPU accelerated rasterization and close-form evaluation (fig. 11). This intermediate representation is hidden from the user: it is dynamically updated using FEM during drawing when control points are edited. We demonstrated novel usages of vector drawings such as instancing, layering, deformation, texture and environment mapping. Finally, we also generalized and extended the set of drawing possibilities, in particular, by showing how to locally control vector gradients. This work has been published at SIGGRAPH Asia [16] and featured by the 3DFV website [24].

5.4.2. Growing Least Squares (GLS) for the Analysis of Manifolds in Scale-Space

We created a novel approach for the multi-scale analysis of point-sampled manifolds of co-dimension 1. It is based on a variant of Moving Least Squares, whereby the evolution of a geometric descriptor at increasing scales is used to locate pertinent locations in scale-space, hence the name "Growing Least Squares (GLS)". Compared to existing scale-space analysis methods, our approach is the first to provide a continuous solution in space and scale dimensions, without requiring any parametrization, connectivity or uniform sampling. An important implication is that we identify multiple pertinent scales for any point on a manifold, a property that had not yet been demonstrated in the literature. In practice, our approach exhibits an improved robustness to change of input, and is easily implemented in a parallel fashion on the GPU, and it can be used in a wide variety of applications. For example, the GLS can be used for the detection of similarity, according to a given scale range (see Figure 12). This work has been published at the Symposium of Geometry Processing [18].

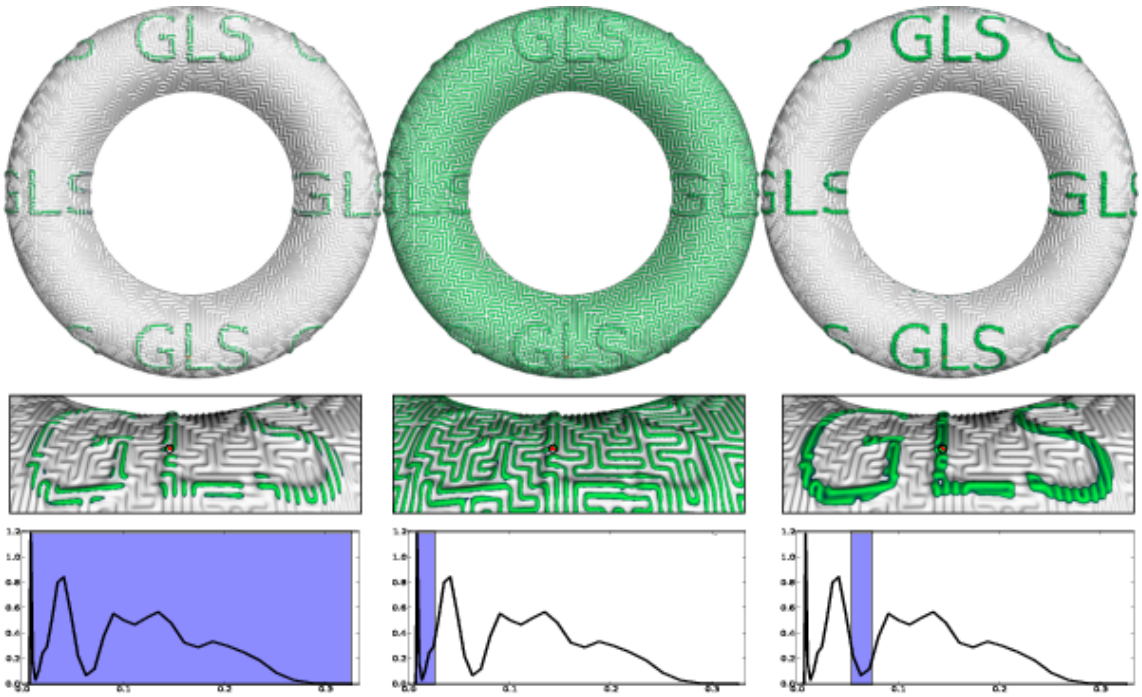


Figure 12. GLS Multi-scale similarity. Top and middle rows: For a selected point (in red), similar points are selected (in green) via our dissimilarity measure. The similarity is computed for each vertex and interpolated per fragment during the rendering. Bottom row: the type of selected feature depends on a user-controlled global prior (shown as a blue box), which is locally refined by our geometric variation. In (a), all scales are selected. In (b), only the fine displacement pattern emerges. In (c), the large-scale GLS letters are properly segmented.

POTIOC Team

6. New Results

6.1. Spatial augmented reality for physical drawing

Participants: Jérémy Laviole, Martin Hachet.

Spatial augmented reality (SAR) promises the integration of digital information in the real (physical) world through projection. We proposed different tools to improve speed or ease the drawing by projecting photos, virtual construction lines and interactive 3D scenes (published in the 3DUI symposium [16]). We explored the creation of tools which help to create drawings that are "difficult" to achieve for a human being, such as stereographic drawings (published in the 3DCHI CHI workshop [18]). Through these tools, we want to apply existing computer graphics techniques to enhance existing drawing tools, and to use it to teach how to draw. Furthermore, we proposed some insights for the creation of digital games and programs which can take full advantages of physical drawings (published in the UIST doctoral symposium [17]).

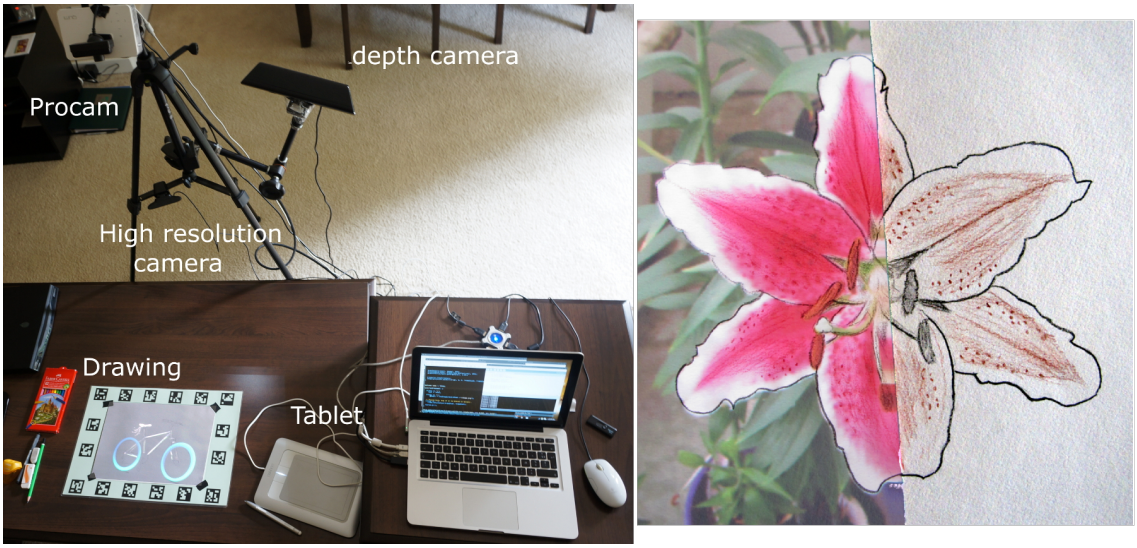


Figure 3. Left: Spatial augmented reality system for physical drawing. Right: Projection of a source image on overlay of an actual drawing, to teach drawing thanks to computer graphic tools [16].

6.2. Brain-Computer Interfaces

Participants: Fabien Lotte, Florian Larrue, Martin Hachet.

As part of our research on Brain-Computer Interfaces (BCI), our contributions addressed two different levels: 1) the brain signal processing level, in order to design more efficient BCI systems and 2) the applications level, in order to propose and explore new BCI applications.

At the signal processing level, we explored and designed new features to represent ElectroEncephaloGraphic (EEG) signals. In particular we explored multifractal cumulants and predictive complexity features (which we published in the Neurocomputing journal [5]), as well as waveform length features together with an optimal spatial filter that we designed for such features (which we published in the ICPR international conference [19]). All these features proved useful to classify EEG signals, and, more importantly, increased the classification performances of the system when combined together with the gold standard features, namely, band power features. Thus, this contributed to extending the repertoire of features available to BCI designers as well as increasing BCI performances. Nevertheless, our studies of BCI and educational research led us to the conclusion that current BCI feedback training approaches (which aimed at teaching people how to use a BCI and how to control their own brain activity), are most probably highly inappropriate and one of the major causes for the limited performances of current BCI - maybe more than signal processing methods. We therefore stressed the need for alternative feedback training approaches for BCI in a publication at the international BBCI workshop [20].

At the application level, we mostly focused on Virtual Reality (VR) related applications. Indeed, together with other groups in the field, we reviewed how BCI and VR could be combined in order to give rise to new applications and to improve BCI designs. This was published in a book chapter dedicated to BCI [22]. Similarly, with international colleagues, we reviewed and envisioned new applications of BCI outside the medical domain, and proposed guidelines to move towards these new applications. This notably includes VR and game applications, user-state monitoring, neuro-evaluation, training and education, cognitive improvement as well as safety and security. This was published in the IEEE Computer journal [8]. Finally, we proposed a new and innovative application of BCI: using it as a tool to study spatial cognition and transfer from VR to real environments. In particular, since BCI can be used to navigate a Virtual Environment (VE) without any motor activity, BCI can be used to assess how much motor activity is really needed to transfer spatial knowledge from a VE to a real one. This is what we did by comparing a BCI and a treadmill in order to teach users a path in a VE and then asking them to retrieve this path in the real world. Contrary to what was believed before, our results showed that motor activity is not necessary to learn a path in VR. We showed that what is really necessary is performing an action, but that this action does not have to be motor, and can be, for instance, cognitive (e.g., imagining hand movements), with a BCI. This was published in the VRST international conference [14].

6.3. Understanding user gestures for touch screen-based 3D User Interfaces

Participants: Aurélie Cohé, Martin Hachet.

In the scope of the ANR project Instinct, we studied how users tend to interact with a touchscreen for interacting with 3D content. Our main contributions were to study user behaviors with a standard touchscreen on the one hand, and with a pressure sensitive touchscreen on the other hand.

Multi-touch interfaces have emerged with the widespread use of smartphones. Although a lot of people interact with 2D applications through touchscreens, interaction with 3D applications remains little explored. Most 3D object manipulation techniques have been created by designers who have generally put users aside from the design creation process. We conducted a user study to better understand how non-technical users tend to interact with a 3D object from touchscreen inputs. The experiment has been conducted while users were manipulating a 3D cube with three viewpoints for rotations, scaling and translations (RST). Sixteen users participated and 432 gestures were analyzed. To classify data, we introduce a taxonomy for 3D manipulation gestures with touchscreens. Then, we identify a set of strategies employed by users to perform the proposed cube transformations. Our findings suggest that each participant uses several strategies with a predominant one. Furthermore, we conducted a study to compare touchscreen and mouse interaction for 3D object manipulations. The results suggest that gestures are different according to the device, and touchscreens are preferred for the proposed tasks. Finally, we propose some guidelines to help designers in the creation of more user friendly tools. This work was published in the Graphics Interface (GI) conference [12] as well as in the Computers and Graphics journal [6].

Figure 4. A user navigating a virtual model of the city of Bordeaux with a BCI, in order to learn a specific path [14].

Moreover, few works have focused on the relation between the manipulated data and the quantity of force applied with the fingers sliding on a touch sensor. In another work, we conducted two user studies to better understand how users manage to control pressure, and how they tend to use this input modality. A first set of experiments allows us to characterize pressure in relation to finger motions. Based on the results of this study, we designed a second set of experiments focusing on the completion of 3D manipulation tasks from 2D gestures. The results indicate that a strong relationship exists between the actions the participants intend to perform, and the quantity of force they apply for 3D object manipulations. This finding opens new promising perspectives to enhance user interfaces dedicated to force-based touch sensors.

All these works were published in the PhD thesis of Aurélie Cohé [4], which was defended on December 13th, 2012.

6.4. Virtual reality for Musical Performance

Participants: Florent Berthaut, Martin Hachet.

Immersive virtual environments open new perspectives for music interaction, notably for the visualization of sound processes and of musical structures, for the navigation in musical compositions, for the manipulation of sound parameters and for musical collaboration. Research conducted by Florent Berthaut and Martin Hachet, in collaboration with Myriam Desainte-Catherine from the SCRIME/LaBRI, explore these new possibilities.

Among the current projects, development of the Drile immersive virtual musical instrument was pursued in order to enable various scenographic setups that will be evaluated in the context of public performance. New perspectives for the Tunnels, 3D widgets for musical modulation (see Figure 6), were published as a Poster in the Proceedings of the Symposium on 3D User Interfaces (3DUI) [10]. Novel 3D selection techniques that take music interaction constraints into account are also being designed.

Another project was conducted with David Janin and Benjamin Martin from the LaBRI on new musical models that will be used to improve the hierarchical musical structures manipulated with Drile. It was published in the International Conference on Semantic Computing [11].

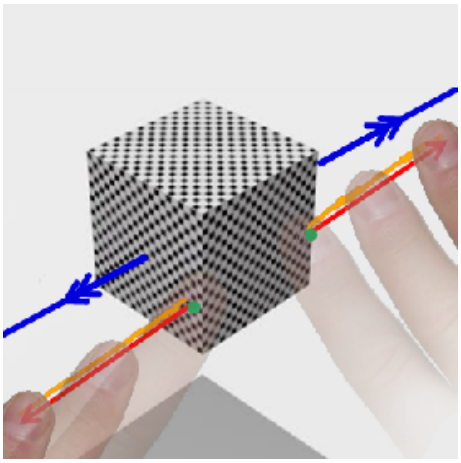


Figure 5. Analysis of users' gestures on touch screen to manipulate 3D content [6].

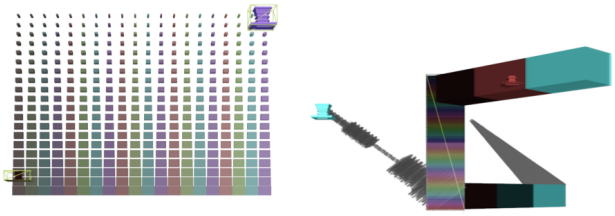


Figure 6. The Tunnels 3D widgets for musical modulation.

A collaboration was started with researchers of the Center for Computer Research on Music and Acoustics (CCRMA) of Stanford University. Florent Berthaut was invited for two months at CCRMA, where he worked with Luke Dahl and Chris Chafe on the implementation of musical collaboration modes in immersive virtual environments. A first result is the design of 3D musical collaboration widgets for Drile, which will be evaluated with musicians.

Another project was initiated with researchers of the Bristol Interaction and Graphics group of the University of Bristol. This project aims at improving the audience experience with Digital Musical Instruments (DMIs). These instruments are often confusing for spectators because of the variety of used components and because of the lack of physical continuity between musicians gestures and the resulting sound. A novel approach was implemented using a mixed-reality system in order to reveal the mechanisms of DMIs (see Figure 7). A description of this approach and of the first prototype will be submitted to the conference on New Interfaces for Musical Expression.

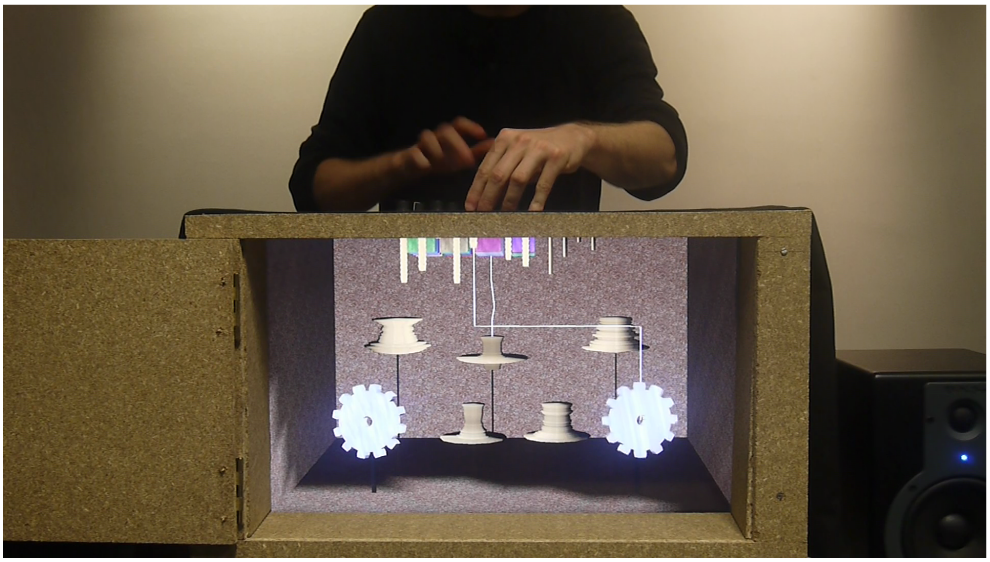


Figure 7. Rouages: a mixed-reality system that reveals the mechanisms of digital musical instruments to the audience.

6.5. Gateway driving simulator

Participants: Florian Larrue, Pauline Davignon, Pierre-Alexandre Favier, Martin Hachet.

As part of the SIMCA FUI project, the POTIOC team focuses on the design and evaluation of a gateway driving simulator, to teach drivers how to drive an airport gateway in virtual reality, i.e., in a safe and cost-effective environment. Gateways are the means to transfer passengers between the airport and the plane, for departures and arrivals. We have developped 3 simulators with different immersion levels (small, medium and immersive simulators, see, e.g., Figure 8). For each immersion level, we developped protocols in order to evaluate the impact of 3D technologies such as stereoscopy and head tracking on users' performances and preferences. Experimentations and evaluations are currently in progress.

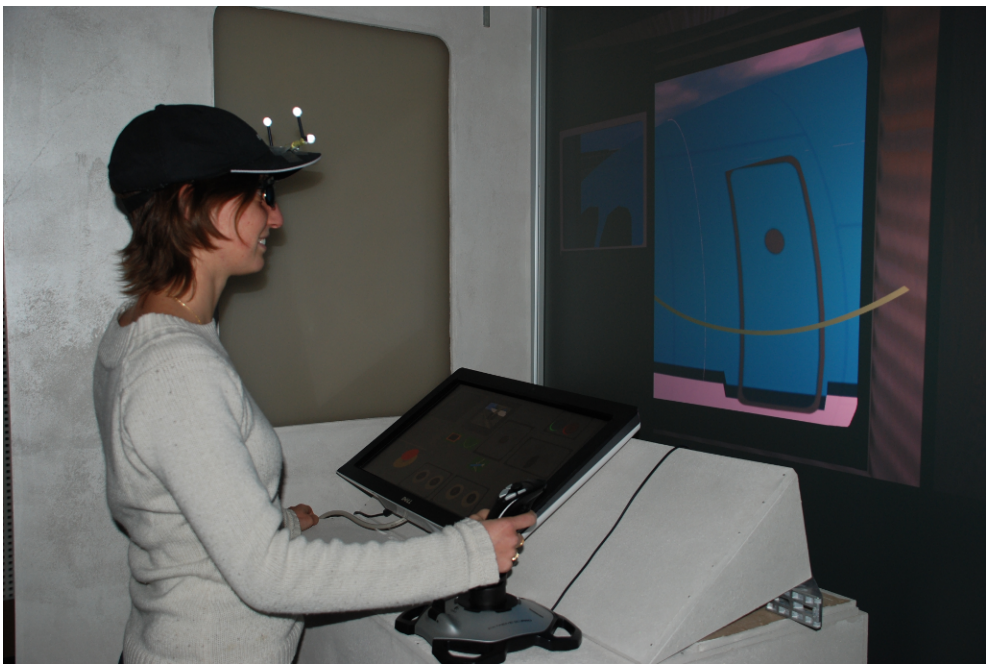


Figure 8. A user, equipped with head tracking and stereoscopic glasses, using the gateway driving simulator.