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FIELD

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ALF Project-Team

3. Research Program

3.1. Motivations

Multicores have become mainstream in general-purpose as well as embedded computing in the last few years. The integration technology trend allows to anticipate that a 1000-core chip will become feasible before 2020. On the other hand, while traditional parallel application domains, e.g. supercomputing and transaction servers, are benefiting from the introduction of multicores, there are very few new parallel applications that have emerged during the last few years.

In order to allow the end-user to benefit from the technological breakthrough, new architectures have to be defined for the 2020's many-cores, new compiler and code generation techniques as well as new performance prediction/guarantee techniques have to be proposed .

3.2. The context

3.2.1. Technological context: The advent of multi- and many- core architecture

For almost 30 years since the introduction of the first microprocessor, the processor industry was driven by the Moore's law till 2002, delivering performance that doubled every 18-24 months on a uniprocessor. However since 2002 , and despite new progress in integration technology, the efforts to design very aggressive and very complex wide issue superscalar processors have essentially been stopped due to poor performance returns, as well as power consumption and temperature walls.

Since 2002-2003, the microprocessor industry has followed a new path for performance: the so-called multicore approach, i.e., integrating several processors on a single chip. This direction has been followed by the whole processor industry. At the same time, most of the computer architecture research community has taken the same path, focusing on issues such as scalability in multicores, power consumption, temperature management and new execution models, e.g. hardware transactional memory.

In terms of integration technology, the current trend will allow to continue to integrate more and more processors on a single die. Doubling the number of cores every two years will soon lead to up to a thousand processor cores on a single chip. The computer architecture community has coined these future processor chips as many-cores.

3.2.2. The application context: multicores, but few parallel applications

For the past five years, small scale parallel processor chips (hyperthreading, dual and quad-core) have become mainstream in general-purpose systems. They are also entering the high-end embedded system market. At the same time, very few (scalable) mainstream parallel applications have been developed. Such development of scalable parallel applications is still limited to niche market segments (scientific applications, transaction servers).

3.2.3. The overall picture

Till now, the end-user of multicores is experiencing improved usage comfort because he/she is able to run several applications at the same time. Eventually, in the near future with the 8-core or the 16-core generation, the end-user will realize that he/she is not experiencing any functionality improvement or performance improvement on current applications. The end-user will then realize that he/she needs more effective performance rather than more cores. The end-user will then ask either for parallel applications or for more effective performance on sequential applications.

3.3. Technology induced challenges

3.3.1. The power and temperatures walls

The power and the temperature walls largely contributed to the emergence of the small-scale multicores. For the past five years, mainstream general-purpose multicores have been built by assembling identical superscalar cores on a chip (e.g. IBM Power series). No new complex power hungry mechanisms were introduced in the core architectures, while power saving techniques such as power gating, dynamic voltage and frequency scaling were introduced. Therefore, since 2002, the designers have been able to keep the power consumption budget and the temperature of the chip within reasonable envelopes while scaling the number of cores with the technology.

Unfortunately, simple and efficient power saving techniques have already caught most of the low hanging fruits on energy consumption. Complex power and thermal management mechanisms are now becoming mainstream; e.g. the Intel Montecito (IA64) featured an adjunct (simple) core whose unique mission is to manage the power and temperature on two cores. Processor industry will require more and more heroic efforts on this power and temperature management policy to maintain its current performance scaling path. Hence the power and temperature walls might slow the race towards 100's and 1000's cores unless the processor industry takes a new paradigm shift from the current "replicating complex cores" (e.g. Intel Nehalem) towards many simple cores (e.g. Intel Larrabee) or heterogeneous manycores (e.g. new GPUs, IBM Cell).

3.3.2. The memory wall

For the past 20 years, the memory access time has been one of the main bottlenecks for performance in computer systems. This was already true for uniprocessors. Complex memory hierarchies have been defined and implemented in order to limit the visible memory access time as well as the memory traffic demands. Up to three cache levels are implemented for uniprocessors. For multi- and many-cores the problems are even worse. The memory hierarchy must be replicated for each core, memory bandwidth must be shared among the distinct cores, data coherency must be maintained. Maintaining cache coherency for up to 8 cores can be handled through relatively simple bus protocols. Unfortunately, these protocols do not scale for large numbers of cores, and there is no consensus on coherency mechanism for manycore systems. Moreover there is no consensus on core organization (flat ring? flat grid? hierarchical ring or grid?).

Therefore, organizing and dimensioning the memory hierarchy will be a major challenge for the computer architects. The successful architecture will also be determined by the abilitty of the applications (i.e., the programmers or the compilers or the run-time) to efficiently place data in the memory hierarchy and achieve high performance.

Finally new technology opportunities may demand to revisit the memory hierarchy. As an example, 3D memory stacking enables a huge last-level cache (maybe several gigabytes) with huge bandwidth (several Kbits/ processor cycle). This dwarfs the main memory bandwidth and may lead to other architectural tradeoffs.

3.4. Need for efficient execution of parallel applications

Achieving high performance on future multicores will require the development of parallel applications, but also an efficient compiler/runtime tool chain to adapt codes to the execution platform.

3.4.1. The diversity of parallelisms

Many potential execution parallelism patterns may coexist in an application. For instance, one can express some parallelism with different tasks achieving different functionalities. Within a task, one can expose different granularities of parallelism; for instance a first layer message passing parallelism (processes executing the same functionality on different parts of the data set), then a shared memory thread level parallelism and fine grain loop parallelism (a.k.a vector parallelism).

Current multicores already feature hardware mechanisms to address these different parallelisms: physically distributed memory — e.g. the new Intel Nehalem already features 6 different memory channels — to address task parallelism, thread level parallelism — e.g. on conventional multicores, but also on GPUs or on Cell-based machines —, vector/SIMD parallelism — e.g. multimedia instructions. Moreover they also attack finer instruction level parallelism and memory latency issues. Compilers have to efficiently discover and manage all these forms to achieve effective performance.

3.4.2. Portability is the new challenge

Up to now, most parallel applications were developed for specific application domains in high end computing. They were used on a limited set of very expensive hardware platforms by a limited number of expert users. Moreover, they were executed in batch mode.

In contrast, the expectation of most end-users of the future mainstream parallel applications running on multicores will be very different. The mainstream applications will be used by thousands, maybe millions of non-expert users. These users consider functional portability of codes as granted. They will expect their codes to run faster on new platforms featuring more cores. They will not be able to tune the application environment to optimize performance. Finally, multiple parallel applications may have to be executed concurrently.

The variety of possible hardware platforms, the lack of expertise of the end-users and the varying run-time execution environments will represent major difficulties for applications in the multicore era.

First of all, the end user considers functional portability without recompilation as granted, this is a major challenge on parallel machines. Performance portability/scaling is even more challenging. It will become inconceivable to rewrite/retune each application for each new parallel hardware platform generation to exploit them. Therefore, apart from the initial development of parallel applications, the major challenge for the next decade will be to *efficiently* run parallel applications on hardware architectures radically different from their original hardware target.

3.4.3. The need for performance on sequential code sections

3.4.3.1. Most software will exhibit substantial sequential code sections

For the foreseeable future, the majority of applications will feature important sequential code sections.

First, many legacy codes were developed for uniprocessors. Most of these codes will not be completely redeveloped as parallel applications, but will evolve to applications using parallel sections for the most compute-intensive parts. Second, the overwhelming majority of the programmers have been educated to program in a sequential programming style. Parallel programming is much more difficult, time consuming and error prone than sequential programming. Debugging and maintaining a parallel code is a major issue. Investing in the development of a parallel application will not be cost-effective for the vast majority of software developments. Therefore, sequential programming style will continue to be dominant in the foreseeable future. Most developers will rely on the compiler to parallelize their application and/or use some software components from parallel libraries.

3.4.3.2. Future parallel applications will require high performance sequential processing on 1000's cores chip

With the advent of universal parallel hardware in multicores, large diffusion parallel applications will have to run on a broad spectrum of parallel hardware platforms. They will be used by non-expert users who will not be able to tune the application environment to optimize performance. They will be executed concurrently with other processes which may be interactive.

The variety of possible hardware platforms, the lack of expertise of the end-user and the varying run-time execution environments are major difficulties for parallel applications. This tends to constrain the programming style and therefore reinforces the sequential structure of the control of the application.

Therefore, *most future parallel applications will rely on a single main thread or a few main threads in charge of distinct functionalities of the application. Each main thread will have a general sequential control and can initiate and control the parallel execution of parallel tasks.*

In 1967, Amdahl [37] pointed out that, if only a portion of an application is accelerated, the execution time cannot be reduced below the execution time of the residual part of the application. Unfortunately, even highly parallelized applications exhibit some residual sequential part. For parallel applications, this indicates that the effective performance of the future 1000's cores chip will significantly depend on their ability to be efficient on the execution of the control portions of the main thread as well as on the execution of sequential portions of the application.

3.4.3.3. The success of 1000's cores architecture will depend on single thread performance

While the current emphasis of computer architecture research is on the definition of scalable multi- many- core architectures for highly parallel applications, we believe that the success of the future 1000-core architecture will depend not only on their performance on parallel applications including sequential sections, but also on their performance on single thread workloads.

3.5. Performance evaluation/guarantee

Predicting/evaluating the performance of an application on a system without explicitly executing the application on the system is required for several usages. Two of these usages are central to the research of the ALF project-team: microarchitecture research (the system to be be evaluated does not exist) and Worst Case Execution Time estimation for real-time systems (the numbers of initial states or possible data inputs is too large).

When proposing a micro-architecture mechanism, its impact on the overall processor architecture has to be evaluated in order to assess its potential performance advantages. For microarchitecture research, this evaluation is generally done through the use of cycle-accurate simulation. Developing such simulators is quite complex and microarchitecture research was helped but also biased by some popular public domain research simulators (e.g. Simplescalar [38]). Such simulations are CPU consuming and simulations cannot be run on a complete application. Sampling representative slices of the application was proposed [4] and popularized by the Simpoint [48] framework.

Real-time systems need a different use of performance prediction; on hard real-time systems, timing constraints must be respected independently from the data inputs and from the initial execution conditions. For such a usage, the Worst Case Execution Time (WCET) of an application must be evaluated and then checked against the timing constraints. While safe and tight WCET estimation techniques and tools exist for reasonably simple embedded processors (e.g. techniques based on abstract interpretation such as [40]), accurate evaluation of the WCET of an algorithm on a complex uniprocessor system is a difficult problem. Accurately modelling data cache behavior [3] and complex superscalar pipelines are still research questions as illustrated by the presence of so-called *timing anomalies* in dynamically scheduled processors, resulting from complex interactions between processor elements (among others, interactions between caching and instruction scheduling) [45].

With the advance of multicores, evaluating / guaranteeing a computer system response time is becoming much more difficult. Interactions between processes occurs at different levels. The execution time on each core depends on the behavior of the other cores. Simulations of 1000's cores micro-architecture will be needed in order to evaluate future many-core proposals. While a few multiprocessor simulators are available for the community, these simulators cannot handle realistic 1000's cores micro-architecture. New techniques have to be invented to achieve such simulations. WCET estimations on multicore platforms will also necessitate radically new techniques, in particular, there are predictability issues on a multicore where many resources are shared; those resources include the memory hierarchy, but also the processor execution units and all the hardware resources if SMT is implemented [52].

3.6. General research directions

The overall performance of a 1000's core system will depend on many parameters including architecture, operating system, runtime environment, compiler technology and application development. In the ALF project, we will essentially focus on architecture, compiler/execution environment as well as performance

predictability, and in particular WCET estimation. Moreover, architecture research, and to a smaller extent, compiler and WCET estimation researches rely on processor simulation. A significant part of the effort in ALF will be devoted to define new processor simulation techniques.

3.6.1. Microarchitecture research directions

We have identified that high performance on single threads and sequential codes is one of the key issues for enabling overall high performance on a 1000's core system and we anticipate that the general architecture of such 1000's core chip will feature many simple cores and a few very complex cores.

Therefore our research in the ALF project will focus on refining the microarchitecture to achieve high performance on single process and/or sequential code sections within the general framework of such an heteregeneous architecture. This leads to two main research directions 1) enhancing the microarchitecture of high-end superscalar processors, 2) exploiting/modifying heterogeneous multicore architecture on a single process. The temperature wall is also a major technological/architectural issue for the design of future processor chips.

3.6.1.1. Enhancing complex core microarchitecture

Research on wide issue superscalar processors was merely stopped around 2002 due to limited performance returns and the power consumption wall.

When considering a heterogeneous architecture featuring hundreds of simple cores and a few complex cores, these two obstacles will partially vanish: 1) the complex cores will represent only a fraction of the chip and a fraction of its power consumption. 2) any performance gain on (critical) sequential threads will result in a performance gain of the whole system

On the complex core, the performance of a sequential code is limited by several factors. At first, on current architectures, it is limited by the peak performance of the processor. To push back this first limitation, we will explore new microarchitecture mechanisms to increase the potential peak performance of a complex core enabling larger instruction issue width. The processor performance is also limited by control dependencies. To push back this limitation, we will explore new branch prediction mechanisms as well as new directions for reducing branch misprediction penalties [10], [12]. As data dependencies may strongly limit performance, we will revisit data prediction. Processor performance is also often highly dependent on the presence or absence of data in a particular level of the memory hierarchy. For the ALF multicore, we will focus on sharing the access to the memory hierarchy in order to adapt the performance of the main thread to the performance of the other cores. All these topics should be studied with the new perspective of quasi unlimited silicon budget.

3.6.1.2. Exploiting heterogeneous multicores on single process

When executing a sequential section on the complex core, the simple cores will be free. Two main research directions to exploit thread level parallelism on a sequential thread have been initiated in late 90's within the context of simultaneous multithreading and early chip multiprocessor proposals: helper threads and speculative multithreading.

Helper threads were initially proposed to improve the performance of the main threads on simultaneous multithreaded architectures [39]. The main idea of helper threads is to execute codes that will accelerate the main thread without modifying its semantic.

In many cases, the compiler cannot determine if two code sections are independent due to some unresolved memory dependency. When no dependency occurs at execution time, the code sections can be executed in parallel. Thread-Level Speculation has been proposed to exploit coarse grain speculative parallelism. Several hardware-only proposals were presented [46], but the most promising solutions integrate hardware support for software thread-level speculation [50].

In the context of future manycores, thread-level speculation and helper threads should be revisited. Many simple cores will be available for executing helper threads or speculative thread execution during the execution of sequential programs or sequential code sections. The availability of these many cores is an opportunity as well as a challenge. For example, one can try to use the simple cores to execute many different helper threads

that could not be implemented within a simultaneous multithreaded processor. For thread level speculation, the new challenge is the use of less powerful cores for speculative threads. Moreover the availability of many simple cores may lead to the use of helper threads and thread level speculation at the same time.

3.6.1.3. Temperature issues

Temperature is one of the constraints that have prevented the processor clock frequency to be increased in recent years. Besides techniques to decrease the power consumption, the temperature issue can be tackled with *dynamic thermal management* [9] through techniques such as clock gating or throttling and *activity migration* [49][5].

Dynamic thermal management (DTM) is now implemented on existing processors. For high performance, processors are dimensioned according to the average situation rather than to the worst case situation. Temperature sensors are used on the chip to trigger dynamic thermal management actions, for instance thermal throttling whenever necessary. On multicores, it is possible to migrate the activity from one core to another in order to limit temperature.

A possible way to increase sequential performance is to take advantage of the smaller gate delay that comes with miniaturization, which permits in theory to increase the clock frequency. However increasing the clock frequency generally requires to increase the instantaneous power density. This is why DTM and activity migration will be key techniques to deal with Amdahl's law in future many-core processors.

3.6.2. Processor simulation research

Architecture studies, and in particular microarchitecture studies, require extensive validations through detailed simulations. Cycle accurate simulators are needed to validate the microarchitectural mechanisms.

Within the ALF project, we can distinguish two major requirements on the simulation: 1) single process and sequential code simulations 2) parallel code sections simulations.

For simulating parallel code sections, a cycle-accurate microarchitecture simulator of a 1000-core architecture will be unacceptably slow. In [6], we showed that mixing analytical modeling of the global behavior of a processor with detailed simulation of a microarchitecture mechanism allows to evaluate this mechanism. Karkhanis and Smith [42] further developed a detailed analytical simulation model of a superscalar processor. Building on top of these preliminary researches, simulation methodology mixing analytical modeling of the simple cores with a more detailed simulation of the complex cores is appealing. The analytical model of the simple cores will aim at approximately modeling the impact of the simple core execution on the shared resources (e.g. data bandwidth, memory hierarchy) that are also used by the complex cores.

Other techniques such as regression modeling [43] can also be used for decreasing the time required to explore the large space of microarchitecture parameter values. We will explore these techniques in the context of many-core simulation.

In particular, research on temperature issues will require the definition and development of new simulation tools able to simulate several minutes or even hours of processor execution, which is necessary for modeling thermal effects faithfully.

3.6.3. Compiler research directions

3.6.3.1. General directions

Compilers are keystone solutions for any approach that deals with high performance on 100+ processors systems. But general-purpose compilers try to embrace so many domains and try to serve so many constraints that they frequently fail to achieve very high performance. They need to be deeply revisited. We identify four main compiler/software related issues that must be addressed in order to allow efficient use of multi- and many-cores: 1) programming 2) resource management 3) application deployment 4) portable performance. Addressing these challenges will require to revisit parallel programming and code generation extensively.

The past of parallel programming is scattered with hundreds of parallel languages. Most of these languages were designed to program homogeneous architectures and were targeting a small and well-trained community of HPC programmers. With the new diversity of parallel hardware platforms and the new community of non-expert developers, expressing parallelism is not sufficient anymore. Resource management, application deployment and portable performance are intermingled issues that require to be addressed holistically.

As many decisions should be taken according to the available hardware, resource management cannot be separated from parallel programming. Deploying applications on various systems without having to deal with thousands of hardware configurations (different numbers of cores, accelerators, ...) will become a major concern for software distribution. The grail of parallel computing is to be able to provide portable performance on a large set of parallel machines and varying execution contexts.

Recent techniques are showing promises. Iterative compilation techniques, exploiting the huge CPU cycle count now available, can be used to explore the optimization space at compile-time. Second, machine-learning techniques can be used to automatically improve compilers and code generation strategies. Speculation can be used to deal with necessary but missing information at compile-time. Finally, dynamic techniques can select or generate at run-time the most efficient code adapted to the execution context and available hardware resources.

Future compilers will benefit from past research, but they will also need to combine static and dynamic techniques. Moreover, domain specific approaches might be needed to ensure success. The ALF research effort will focus on these static and dynamic techniques to address the multicore application development challenges.

3.6.3.2. Portability of applications and performance through virtualization

The life cycle is much longer for applications than for hardware. Unfortunately the multicore era jeopardizes the old binary compatibility recipe. Binaries cannot automatically exploit additional computing cores or new accelerators available on the silicon. Moreover maintaining backward binary compatibility on future parallel architectures will rapidly become a nightmare, applications will not run at all unless some kind of dynamic binary translation is at work.

Processor virtualization addresses the problem of portability of functionalities. Applications are not compiled to the final native code but to a target independent format. This is the purpose of languages such as Java and .NET. Bytecode formats are often *a priori* perceived as inappropriate for performance intensive applications and for embedded systems. However, it was shown that compiling a C or C++ program to a bytecode format produces a code size similar to dense instruction sets [2]. Moreover, this bytecode representation can be compiled to native code with performance similar to static compilation [1]. Therefore processor virtualization for high performance, i.e., for languages like C or C++, provides significant advantages: 1) it simplifies software engineering with fewer tools to maintain and upgrade; 2) it allows better code readability and easier code maintenance since it avoids code specialization for specific targets using compile time macros such as #ifdef ; 3) the *execution code* deployed on the system is the execution code that has been debugged and validated, as opposed to the same *source code* has been recompiled for another platform; 4) new architectures will come with their JIT compiler. The JIT will (should) automatically take advantage of new architecture features such as SIMD/vector instructions or extra processors.

Our objective is to enrich processor virtualization to allow both functional portability and high performance using JIT at runtime, or bytecode-to-native code offline compiler. Split compilation can be used to annotate the bytecode with relevant information that can be helpful to the JIT at runtime or to the bytecode to native code offline compiler. Because the first compilation pass occurs offline, aggressive analyses can be run and their outcomes encoded in the bytecode. For example, such information include vectorizability, memory references (in)dependencies, suggestions derived from iterative compilation, polyhedral analysis, or integer linear programming. Virtualization allows to postpone some optimizations to run time, either because they increase the code size and would increase the cost of an embedded system or because the actual hardware platform characteristics are unknown.

3.6.4. Performance predictability for real-time systems

While compiler and architecture research efforts often focus on maximizing average case performance, applications with real-time constraints do not need only high performance but also performance guarantees in all situations, including the worst-case situation. Worst-Case Execution Time estimates (WCET) need to be upper bounds of any possible execution time. The safety level required depends on the criticality of applications: missing a frame on a video in the airplane for passenger in seat 20B is less critical than a safety critical decision in the control of the airplane.

Within the ALF project, our objective is to study performance guarantees for both (i) sequential codes running on complex cores ; (ii) parallel codes running on the multicores. This results in two quite distinct problems.

For sequential code executing on a single core, one can expect that, in order to provide real-time possibility, the architecture will feature an execution mode where a given processor will be guaranteed to access a fixed portion of the shared resources (caches, memory bandwidth). Moreover, this guaranteed share could be optimized at compile time to enforce the respect of the time constraints. However, estimating the WCET of an application on a complex micro-architecture is still a research challenge. This is due to the complex interaction of micro-architectural elements (superscalar pipelines, caches, branch prediction, out-of-order execution) [45]. We will continue to explore pure analytical and static methods. However when accurate static hardware modeling methods cannot handle the hardware complexity, new probabilistic methods [44] might be needed to explore to obtain as safe as possible WCET estimates.

Providing performance guarantees for parallel applications executed on a multicore is a new and challenging issue. Entirely new WCET estimation methods have to be defined for these architectures to cope with dynamic resource sharing between cores, in particular on-chip memory (either local memory or caches) are shared, but also buses, network-on-chip and the access to the main memory. Current pure analytical methods are too pessimistic at capturing interferences between cores [53], therefore hardware-based or compiler methods such as [51] have to be defined to provide some degree of isolation between cores. Finally, similarly to simulation methods, new techniques to reduce the complexity of WCET estimation will be explored to cope with manycore architectures.

CAIRN Project-Team

3. Research Program

3.1. Panorama

The development of complex applications is traditionally split in three stages: a theoretical study of the algorithms, an analysis of the target architecture and the implementation. When facing new emerging applications such as high-performance, low-power and low-cost mobile communication systems or smart sensor-based systems, it is mandatory to strengthen the design flow by a joint study of both algorithmic and architectural issues [0].

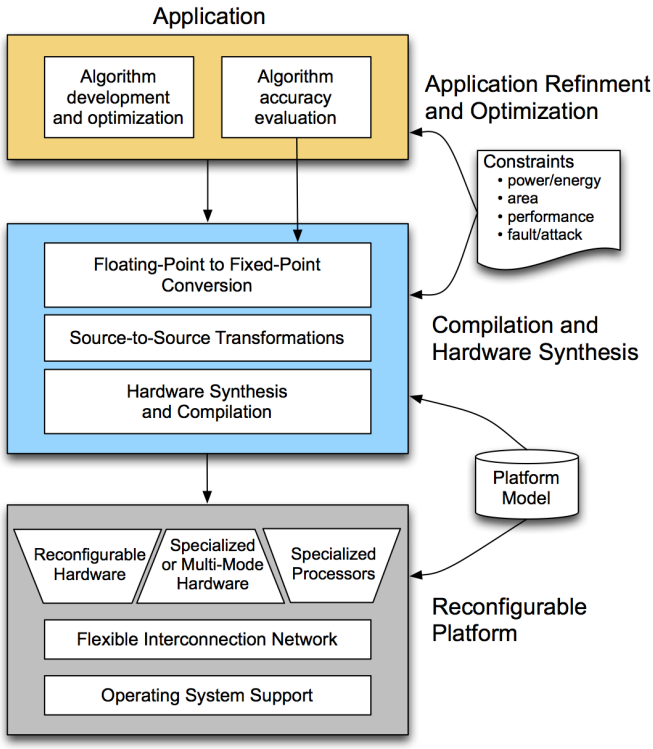

Figure 1. CAIRN*'s general design flow and related research themes*

Figure 1 shows the global design flow we propose to develop. This flow is organized in levels which refer to our three research themes: application optimization (new algorithms, fixed-point arithmetic and advanced representations of numbers), architecture optimization (reconfigurable and specialized hardware, application-specific processors), and stepwise refinement and code generation (code transformations, hardware synthesis, compilation).

[0] Often referenced as algorithm-architecture mapping or interaction.

In the rest of this part, we briefly describe the challenges concerning **new reconfigurable platforms** in Section 3.2 , the issues on **compiler and synthesis tools** related to these platforms in Section 3.3 , and the remaining challenges in **algorithm architecture interaction** in Section 3.4 .

3.2. Reconfigurable Architecture Design

Over the last two decades, there has been a strong push of the research community to evolve static programmable processors into run-time dynamic and partial reconfigurable (DPR) architectures. Several research groups around the world have hence proposed reconfigurable hardware systems operating at various levels of granularity. For example, functional-level reconfiguration has been proposed to increase the efficiency of programmable processors without having to pay for the FPGAs penalties. These coarse-grained reconfigurable architectures (CGRAs) provide operator-level configurable functional blocks and word-level datapaths. The main goal of this class of architectures is to provide flexibility while minimizing reconfiguration overhead (there exists several recent surveys on this topic [113], [97], [78], [114]). Compared to fine-grained architectures, CGRAs benefit from a massive reduction in configuration memory and configuration delay, as well as a considerable reduction in routing and placement complexity. This, in turns, results in an improvement in the computation volume over energy cost ratio, even if it comes at the price of a loss of flexibility compared to bit-level operations. Such constraints have been taken into account in the design of DART [93][12], CRIP [81], Adres [105] or others [116]. These works have led to commercial products such as the Extreme Processor Platform (XPP) [82] from PACT or Montium [0] from Recore systems.

Another strong trend is the design of hybrid architectures which combine standard GPP or DSP cores with arrays of *configurable elements* such as the Lx [96], or of *field-configurable elements* such as the Xirisc processor [103] and more recently by commercial platforms such as the Xilinx Zynq-7000. Some of their benefits are the following: functionality on demand (set-top boxes for digital TV equipped with decoding hardware on demand), acceleration on demand (coprocessors that accelerate computationally demanding applications in multimedia or communications applications), and shorter time-to-market (products that target ASIC platforms can be released earlier using reconfigurable hardware).
Dynamic reconfiguration enables an architecture to adapt itself to various incoming tasks. This requires complex resource management and control which can be provided as services by a real-time operating system (RTOS) [104]: communication, memory management, task scheduling [92], [85][1] and task placement. Such an Operating System (OS) based approach has many advantages: it provides a complete design framework, that is independent of the technology and of the underlying hardware architecture, helping to drastically reduce the full platform design time. Due to the unpredictable execution of tasks, the OS must be able to allocate resource to tasks at run-time along with mechanisms to support inter-task communication. An efficient way to support such communications is to resort to a network-on-chip [111]. The role of the communication infrastructure is then to support transactions between different components of the platform, either between macro-components – main processor, dedicated modules, dynamically reconfigurable component – or within the elements of the reconfigurable components themselves.

In CAIRNwe mainly target reconfigurable system-on-chip (RSoC) defined as a set of computing and storing resources organized around a flexible interconnection network and integrated within a single silicon chip (or programmable chip such as FPGAs). The architecture is customized for an application domain, and the flexibility is provided by both hardware reconfiguration and software programmability. Computing resources are therefore highly heterogeneous and raise many issues that we discuss in the following:

- **Reconfigurable hardware blocks with a dynamic behavior** where reconfigurability can be achieved at the bit- or operator-level. Our research aims at defining new reconfigurable architectures including computing and memory resources. Since reconfiguration must happen as fast as possible (typically within a few cycles), reducing the configuration time overhead is also a key issue.

[0] http://www.recoresystems.com/

- When performance and power consumption are major constraints, it is acknowledged that optimized specialized hardware blocks (often called IPs for Intellectual Properties) are the best (and often the only) solution. Therefore, we also study architecture and tools for **specialized hardware accelerators** and for **multi-mode components**.
- Customized **processors with a specialized instruction-set** also offer a viable solution to trade between energy efficiency and flexibility. They are particularly relevant for modern FPGA platforms where many processor cores can be embedded. For this topic, we focus on the automatic generation of heterogeneous (sequential or parallel) reconfigurable processor extensions that are tightly coupled to processor cores.

3.3. Compilation and Synthesis for Reconfigurable Platforms

In spite of their advantages, reconfigurable architectures lack efficient and standardized compilation and design tools. As of today, this still makes the technology impractical for large scale industrial use. Generating and optimizing the mapping from high-level specifications to reconfigurable hardware platforms is therefore a key research issue, and the problem has received considerable interest over the last years [108], [84], [115], [118]. In the meantime, the complexity (and heterogeneity) of these platforms has also been increasing quite significantly, with complex heterogeneous multi-cores architectures becoming a *de facto* standard. As a consequence, the focus of designers is now geared toward optimizing overall system-level performance and efficiency [99], [108], [107]. Here again, existing tools are not well suited, as they fail at providing a unified programming view of the programmable and/or reconfigurable components implemented on the platform.
In this context we have been pursuing our efforts to propose tools whose design principles are based on a tight coupling between the compiler and the target hardware architectures. We build on the expertise of the team members in High Level Synthesis (HLS) [8], ASIP optimizing compilers [15] and automatic parallelization for massively parallel specialized circuits [6]. We first study how to increase the efficiency of standard programmable processors by extending their instruction set to speed-up computationally-intensive kernels. Our focus is on efficient and exact algorithms for the identification, selection and scheduling of such instructions [9]. We also propose techniques to synthesize reconfigurable (or multi-mode) architectures. We address these challenges by borrowing techniques from high-level synthesis, optimizing compilers and automatic parallelization, especially when dealing with nested loop kernels. The goal is then either to derive a custom fine-grain parallel architecture and/or to derive the configuration of a Coarse Grain Reconfigurable Architecture (CGRA). In addition, and independently of the scientific challenges mentioned above, proposing such flows also poses significant software engineering issues. As a consequence, we also study how leading edge Object Oriented software engineering techniques (Model Driven Engineering) can help the Computer Aided Design (CAD) and optimizing compiler communities prototyping new research ideas.
Efficient implementation of multimedia and signal processing applications (in software for DSP cores or as special-purpose hardware) often requires, for reasons related to cost, power consumption or silicon area constraints, the use of fixed-point arithmetic, whereas the algorithms are usually specified in floating-point arithmetic. Unfortunately, fixed-point conversion is very challenging and time-consuming, typically demanding up to 50% of the total design or implementation time [86]. Thus, tools are required to automate this conversion. For hardware or software implementation, the aim is to optimize the fixed-point specification. The implementation cost is minimized under a numerical accuracy or an application performance constraint. For DSP-software implementation, methodologies have been proposed [101], [106] to achieve a conversion leading to an ANSI-C code with integer data types. For hardware implementation, the best results are obtained when the word-length optimization process is coupled with the high-level synthesis [100], [89]. Evaluating the effects of finite precision is one of the major and often the most time consuming step while performing fixed-point refinement. Indeed, in the word-length optimization process, the numerical accuracy is evaluated as soon as a new word-length is tested, thus, several times per iteration of the optimization process. Classical approaches are based on fixed-point simulations [90], [112]. They lead to long evaluation times and cannot be used to explore the entire design space. Therefore, our aim is to propose closed-form expressions of errors due to fixed-point approximations that are used by a fast analytical framework for accuracy evaluation.

3.4. Interaction between Algorithms and Architectures

As CAIRN mainly targets domain-specific system-on-chip including reconfigurable capabilities, algorithmic-level optimizations have a great potential on the efficiency of the overall system. Based on the skills and experiences in "signal processing and communications" of some CAIRN's members, we conduct research on algorithmic optimization techniques under two main constraints: energy consumption and computation accuracy; and for two main application domains: fourth-generation (4G) mobile communications and wireless sensor networks (WSN). These application domains are very conducive to our research activities. The high complexity of the first one and the stringent power constraint of the second one, require the design of specific high-performance and energy-efficient SoCs. We also consider other applications such as video or bioinformatics, but this short state-of-the-art will be limited to wireless applications.

The radio in both transmit and receive modes consumes the bulk of the total power consumption of the system. Therefore, protocol optimization is one of the main sources of significant energy reduction to be able to achieve self-powered autonomous systems. Reducing power due to radio communications can be achieved by two complementary main objectives: (i) minimizing the output transmit power while maintaining sufficient wireless link quality and (ii) minimizing useless wake-up and channel hearing while still being reactive.

As the physical layer affects all higher layers in the protocol stack, it plays an important role in the energy-constrained design of WSNs. The question to answer can be summarized as: *how much signal processing can be added to decrease the transmission energy (i.e. the output power level at the antenna) such that the global energy consumption be decreased?* The temporal and spatial diversity of relay and multiple antenna techniques are very attractive due to their simplicity and their performance for wireless transmission over fading channels. Cooperative MIMO (multiple-input and multiple-output) techniques have been first studied in [94], [102] and have shown their efficiency in terms of energy consumption [91]. Our research aims at finding new energy-efficient cooperative protocols associating distributed MIMO with opportunistic and/or multiple relays and considering wireless channel impairments such as transmitters desynchronisation.

Another way to reduce the energy consumption consists in decreasing the radio activity, controlled by the medium access (MAC) layer protocols. In this regard, low duty-cycle protocols, such as preamble-sampling MAC protocols, are very efficient because they improve the lifetime of the network by reducing the unnecessary energy waste [80]. As the network parameters (data rate, topology, etc.) can vary, we propose new adaptive MAC protocols to avoid overhearing and idle listening.

Finally, MIMO precoding is now recognized as a very interesting technique to enhance the data rate in wireless systems, and is already used in Wi-Max standard (802.16e). This technique can also be used to reduce transmission energy for the same transmission reliability and the same throughput requirement. One of the most efficient precoders is based on the maximization of the minimum Euclidean distance ($\max$-d_{min}) between two received data vectors [87], but it is difficult to define the closed-form of the optimized precoding matrix for large MIMO system with high-order modulations. Our goal is to derive new generic precoders with simple expressions depending only on the channel angle and the modulation order.

CELTIQUE Project-Team

3. Research Program

3.1. Static program analysis

Static program analysis is concerned with obtaining information about the run-time behaviour of a program without actually running it. This information may concern the values of variables, the relations among them, dependencies between program values, the memory structure being built and manipulated, the flow of control, and, for concurrent programs, synchronisation among processes executing in parallel. Fully automated analyses usually render approximate information about the actual program behaviour. The analysis is correct if the information includes all possible behaviour of a program. Precision of an analysis is improved by reducing the amount of information describing spurious behaviour that will never occur.

Static analysis has traditionally found most of its applications in the area of program optimisation where information about the run-time behaviour can be used to transform a program so that it performs a calculation faster and/or makes better use of the available memory resources. The last decade has witnessed an increasing use of static analysis in software verification for proving invariants about programs. The Celtique project is mainly concerned with this latter use. Examples of static analysis include:

- Data-flow analysis as it is used in optimising compilers for imperative languages. The properties can either be approximations of the values of an expression ("the value of variable x is greater than 0" or x is equal to y at this point in the program") or more intensional information about program behaviour such as "this variable is not used before being re-defined" in the classical "dead-variable" analysis [72].
- Analyses of the memory structure includes shape analysis that aims at approximating the data structures created by a program. Alias analysis is another data flow analysis that finds out which variables in a program addresses the same memory location. Alias analysis is a fundamental analysis for all kinds of programs (imperative, object-oriented) that manipulate state, because alias information is necessary for the precise modelling of assignments.
- Control flow analysis will find a safe approximation to the order in which the instructions of a program are executed. This is particularly relevant in languages where parameters or functions can be passed as arguments to other functions, making it impossible to determine the flow of control from the program syntax alone. The same phenomenon occurs in object-oriented languages where it is the class of an object (rather than the static type of the variable containing the object) that determines which method a given method invocation will call. Control flow analysis is an example of an analysis whose information in itself does not lead to dramatic optimisations (although it might enable in-lining of code) but is necessary for subsequent analyses to give precise results.

Static analysis possesses strong **semantic foundations**, notably abstract interpretation [54], that allow to prove its correctness. The implementation of static analyses is usually based on well-understood constraint-solving techniques and iterative fixpoint algorithms. In spite of the nice mathematical theory of program analysis and the solid algorithmic techniques available one problematic issue persists, *viz.*, the *gap* between the analysis that is proved correct on paper and the analyser that actually runs on the machine. While this gap might be small for toy languages, it becomes important when it comes to real-life languages for which the implementation and maintenance of program analysis tools become a software engineering task. A *certified static analysis* is an analysis that has been formally proved correct using a proof assistant.

In previous work we studied the benefit of using abstract interpretation for developing **certified static analyses** [52], [75]. The development of certified static analysers is an ongoing activity that will be part of the Celtique project. We use the Coq proof assistant which allows for extracting the computational content of a constructive proof. A Caml implementation can hence be extracted from a proof of existence, for any program, of a correct approximation of the concrete program semantics. We have isolated a theoretical framework based on abstract interpretation allowing for the formal development of a broad range of static analyses. Several case studies for the analysis of Java byte code have been presented, notably a memory usage analysis [53]. This work has recently found application in the context of Proof Carrying Code and have also been successfully applied to particular form of static analysis based on term rewriting and tree automata [5].

3.1.1. Static analysis of Java

Precise context-sensitive control-flow analysis is a fundamental prerequisite for precisely analysing Java programs. Bacon and Sweeney's Rapid Type Analysis (RTA) [45] is a scalable algorithm for constructing an initial call-graph of the program. Tip and Palsberg [80] have proposed a variety of more precise but scalable call graph construction algorithms *e.g.,* MTA, FTA, XTA which accuracy is between RTA and 0'CFA. All those analyses are not context-sensitive. As early as 1991, Palsberg and Schwartzbach [73], [74] proposed a theoretical parametric framework for typing object-oriented programs in a context-sensitive way. In their setting, context-sensitivity is obtained by explicit code duplication and typing amounts to analysing the expanded code in a context-insensitive manner. The framework accommodates for both call-contexts and allocation-contexts.

To assess the respective merits of different instantiations, scalable implementations are needed. For Cecil and Java programs, Grove *et al.,* [61], [60] have explored the algorithmic design space of contexts for benchmarks of significant size. Latter on, Milanova *et. al.,* [67] have evaluated, for Java programs, a notion of context called *object-sensitivity* which abstracts the call-context by the abstraction of the `this` pointer. More recently, Lhotak and Hendren [65] have extended the empiric evaluation of object-sensitivity using a BDD implementation allowing to cope with benchmarks otherwise out-of-scope. Besson and Jensen [49] proposed to use DATALOG in order to specify context-sensitive analyses. Whaley and Lam [81] have implemented a context-sensitive analysis using a BDD-based DATALOG implementation.

Control-flow analyses are a prerequisite for other analyses. For instance, the security analyses of Livshits and Lam [66] and the race analysis of Naik, Aiken [68] and Whaley [69] both heavily rely on the precision of a control-flow analysis.

Control-flow analysis allows to statically prove the absence of certain run-time errors such as "message not understood" or cast exceptions. Yet it does not tackle the problem of "null pointers". Fahnrich and Leino [57] propose a type-system for checking that after object creation fields are non-null. Hubert, Jensen and Pichardie have formalised the type-system and derived a type-inference algorithm computing the most precise typing [64]. The proposed technique has been implemented in a tool called NIT [63]. Null pointer detection is also done by bug-detection tools such as FindBugs [63]. The main difference is that the approach of findbugs is neither sound nor complete but effective in practice.

3.1.2. Quantitative aspects of static analysis

Static analyses yield qualitative results, in the sense that they compute a safe over-approximation of the concrete semantics of a program, w.r.t. an order provided by the abstract domain structure. Quantitative aspects of static analysis are two-sided: on one hand, one may want to express and verify (compute) quantitative properties of programs that are not captured by usual semantics, such as time, memory, or energy consumption; on the other hand, there is a deep interest in quantifying the precision of an analysis, in order to tune the balance between complexity of the analysis and accuracy of its result.

The term of quantitative analysis is often related to probabilistic models for abstract computation devices such as timed automata or process algebras. In the field of programming languages which is more specifically addressed by the Celtique project, several approaches have been proposed for quantifying resource usage: a non-exhaustive list includes memory usage analysis based on specific type systems [62], [44], linear

logic approaches to implicit computational complexity [46], cost model for Java byte code [40] based on size relation inference, and WCET computation by abstract interpretation based loop bound interval analysis techniques [55].

We have proposed an original approach for designing static analyses computing program costs: inspired from a probabilistic approach [76], a quantitative operational semantics for expressing the cost of execution of a program has been defined. Semantics is seen as a linear operator over a dioid structure similar to a vector space. The notion of long-run cost is particularly interesting in the context of embedded software, since it provides an approximation of the asymptotic behaviour of a program in terms of computation cost. As for classical static analysis, an abstraction mechanism allows to effectively compute an over-approximation of the semntics, both in terms of costs and of accessible states [51]. An example of cache miss analysis has been developed within this framework [79].

3.2. Software certification

The term "software certification" has a number of meanings ranging from the formal proof of program correctness via industrial certification criteria to the certification of software developers themselves! We are interested in two aspects of software certification:

- industrial, mainly process-oriented certification procedures
- software certificates that convey semantic information about a program

Semantic analysis plays a role in both varieties.

Criteria for software certification such as the Common criteria or the DOA aviation industry norms describe procedures to be followed when developing and validating a piece of software. The higher levels of the Common Criteria require a semi-formal model of the software that can be refined into executable code by traceable refinement steps. The validation of the final product is done through testing, respecting criteria of coverage that must be justified with respect to the model. The use of static analysis and proofs has so far been restricted to the top level 7 of the CC and has not been integrated into the aviation norms.

3.2.1. Process-oriented software certification

The testing requirements present in existing certification procedures pose a challenge in terms of the automation of the test data generation process for satisfying functional and structural testing requirements. For example, the standard document which currently governs the development and verification process of software in airborne system (DO-178B) requires the coverage of all the statements, all the decisions of the program at its higher levels of criticality and it is well-known that DO-178B structural coverage is a primary cost driver on avionics project. Although they are widely used, existing marketed testing tools are currently restricted to test coverage monitoring and measurements [0] but none of these tools tries to find the test data that can execute a given statement, branch or path in the source code. In most industrial projects, the generation of structural test data is still performed manually and finding automatic methods for this problem remains a challenge for the test community. Building automatic test case generation methods requires the development of precise semantic analysis which have to scale up to software that contains thousands of lines of code.

Static analysis tools are so far not a part of the approved certification procedures. For this to change, the analysers themselves must be accepted by the certification bodies in a process called “Qualification of the tools” in which the tools are shown to be as robust as the software it will certify. We believe that proof assistants have a role to play in building such certified static analysis as we have already shown by extracting provably correct analysers for Java byte code.

[0] Coverage monitoring answers to the question: what are the statements or branches covered by the test suite ? While coverage measurements answers to: how many statements or branches have been covered ?

3.2.2. Semantic software certificates

The particular branch of information security called "language-based security" is concerned with the study of programming language features for ensuring the security of software. Programming languages such as Java offer a variety of language constructs for securing an application. Verifying that these constructs have been used properly to ensure a given security property is a challenge for program analysis. One such problem is confidentiality of the private data manipulated by a program and a large group of researchers have addressed the problem of tracking information flow in a program in order to ensure that *e.g.*, a credit card number does not end up being accessible to all applications running on a computer [78], [48]. Another kind of problems concern the way that computational resources are being accessed and used, in order to ensure that a given access policy is being implemented correctly and that a given application does not consume more resources that it has been allocated. Members of the Celtique team have proposed a verification technique that can check the proper use of resources of Java applications running on mobile telephones [50]. **Semantic software certificates** have been proposed as a means of dealing with the security problems caused by mobile code that is downloaded from foreign sites of varying trustworthiness and which can cause damage to the receiving host, either deliberately or inadvertently. These certificates should contain enough information about the behaviour of the downloaded code to allow the code consumer to decide whether it adheres to a given security policy.

Proof-Carrying Code (PCC) [70] is a technique to download mobile code on a host machine while ensuring that the code adheres to a specified security policy. The key idea is that the code producer sends the code along with a proof (in a suitably chosen logic) that the code is secure. Upon reception of the code and before executing it, the consumer submits the proof to a proof checker for the logic. Our project focus on two components of the PCC architecture: the proof checker and the proof generator.

In the basic PCC architecture, the only components that have to be trusted are the program logic, the proof checker of the logic, and the formalization of the security property in this logic. Neither the mobile code nor the proposed proof—and even less the tool that generated the proof—need be trusted.

In practice, the *proof checker* is a complex tool which relies on a complex Verification Condition Generator (VCG). VCGs for real programming languages and security policies are large and non-trivial programs. For example, the VCG of the Touchstone verifier represents several thousand lines of C code, and the authors observed that "there were errors in that code that escaped the thorough testing of the infrastructure" [71]. Many solutions have been proposed to reduce the size of the trusted computing base. In the *foundational proof carrying code* of Appel and Felty [43], [42], the code producer gives a direct proof that, in some "foundational" higher-order logic, the code respects a given security policy. Wildmoser and Nipkow [83], [82]. prove the soundness of a *weakest precondition* calculus for a reasonable subset of the Java bytecode. Necula and Schneck [71] extend a small trusted core VCG and describe the protocol that the untrusted verifier must follow in interactions with the trusted infrastructure.

One of the most prominent examples of software certificates and proof-carrying code is given by the Java byte code verifier based on *stack maps*. Originally proposed under the term “lightweight Byte Code Verification” by Rose [77], the techniques consists in providing enough typing information (the stack maps) to enable the byte code verifier to check a byte code in one linear scan, as opposed to inferring the type information by an iterative data flow analysis. The Java Specification Request 202 provides a formalization of how such a verification can be carried out.

Inspired by this, Albert *et al.* [41] have proposed to use static analysis (in the form of abstract interpretation) as a general tool in the setting of mobile code security for building a proof-carrying code architecture. In their *abstraction-carrying code* framework, a program comes equipped with a machine-verifiable certificate that proves to the code consumer that the downloaded code is well-behaved.

3.2.3. Certified static analysis

In spite of the nice mathematical theory of program analysis (notably abstract interpretation) and the solid algorithmic techniques available one problematic issue persists, *viz.*, the *gap* between the analysis that is proved correct on paper and the analyser that actually runs on the machine. While this gap might be small for

toy languages, it becomes important when it comes to real-life languages for which the implementation and maintenance of program analysis tools become a software engineering task.

A *certified static analysis* is an analysis whose implementation has been formally proved correct using a proof assistant. Such analysis can be developed in a proof assistant like Coq [39] by programming the analyser inside the assistant and formally proving its correctness. The Coq extraction mechanism then allows for extracting a Caml implementation of the analyser. The feasibility of this approach has been demonstrated in [7].

We also develop this technique through certified reachability analysis over term rewriting systems. Term rewriting systems are a very general, simple and convenient formal model for a large variety of computing systems. For instance, it is a very simple way to describe deduction systems, functions, parallel processes or state transition systems where rewriting models respectively deduction, evaluation, progression or transitions. Furthermore rewriting can model every combination of them (for instance two parallel processes running functional programs).

Depending on the computing system modelled using rewriting, reachability (and unreachability) permits to achieve some verifications on the system: respectively prove that a deduction is feasible, prove that a function call evaluates to a particular value, show that a process configuration may occur, or that a state is reachable from the initial state. As a consequence, reachability analysis has several applications in equational proofs used in the theorem provers or in the proof assistants as well as in verification where term rewriting systems can be used to model programs.

For proving unreachability, i.e. safety properties, we already have some results based on the over-approximation of the set of reachable terms [58], [59]. We defined a simple and efficient algorithm [56] for computing exactly the set of reachable terms, when it is regular, and construct an over-approximation otherwise. This algorithm consists of a *completion* of a *tree automaton*, taking advantage of the ability of tree automata to finitely represent infinite sets of reachable terms.

To certify the corresponding analysis, we have defined a checker guaranteeing that a tree automaton is a valid fixpoint of the completion algorithm. This consists in showing that for all term recognised by a tree automaton all his rewrites are also recognised by the same tree automaton. This checker has been formally defined in Coq and an efficient Ocaml implementation has been automatically extracted [5]. This checker is now used to certify all analysis results produced by the regular completion tool as well as the optimised version of [47].

ESTASYS Exploratory Action

3. Research Program

3.1. Systems of Systems, Heterogeneous Systems, Dynamicity, Statistical Model Checking

Formal methods rely on the notion of *transition system* (TS): an abstract machine that characterises a system's *complete* behaviour. This machine consists of a complete set of states (each representing full knowledge of the system at a given moment) and transitions between states, which may be labelled with labels chosen from some set of actions. This definition makes it necessary to have advanced knowledge of all the possible states of the system – to have a statically configured system. The algorithms used by formal methods perform an exhaustive exploration of the state space of the TS, so such methods suffer from the so-called *state-space explosion problem*. As a consequence, there are many real systems that are beyond the scope of such techniques. Despite this, over the last thirty years it has been shown that, when combined with heuristics such as partial order reductions or abstraction, **formal approaches are powerful enough to verify industrial-scale systems**.

The first wave of techniques was deployed to verify whether a certain set of (problem) states can be reached ('reachability'). Later, extensions of TS, such as *hybrid systems* and *stochastic automata*, were proposed to cope with new problems (e.g., energy consumption) or to reason on distributed real-time embedded components (possibly heterogeneous). It was quickly observed that the complexity of assessing correctness of such extended models arises not exclusively from the fact that they are large, but also because they introduce *undecidability*. As a concrete example, the reachability problem is already undecidable for any real-time system whose time evolution is described by a non-constant derivative equation.

This motivated the development of more efficient techniques that approximate the answer to the original problem or approximate the problem. Of these, perhaps the most successful quantitative technique is *Statistical Model Checking* , that can be seen as a trade-off between testing and formal verification. The core idea of SMC is to generate a number of *simulations* of the system and verify whether they satisfy a given property expressed in temporal logics, which can be done by using *runtime verification approaches*. The results are then used together with algorithms from the statistical area in order to decide whether the system satisfies the property with some probability. SMC resembles classical simulation-based techniques used in industry, but uses a formal model of systems and requirements. This not only gives a rigorous meaning to industrial practices, but also makes available more than twenty years of research in the area of *runtime verification*. Last but not least, **the use of statistical algorithms allows us to approximate undecidable problems**. Recent successful applications of SMC can be found in systems biology, security protocols and avionics. In particular, SMC was used to discover inconsistent requirements of an EADS airplane communication system.

3.1.1. Systems of Systems (SoS)

The advent of service-oriented and cloud architectures is leading to generations of computer systems that exhibit a new type of complexity: such systems are no longer statically configured, but comprise components that are systems in their own right, able to discover, select and bind on-the-fly to other components that can deliver services that they require. These complex systems, referred to as *Systems of Systems* (SoS), can change over time as each component creates and modifies the network over which it needs to operate: as they execute, the components create a network of their own and use it to fulfil their goals.

The Internet, made up of an unsupervised and rapidly growing, dynamically configured set of computers and physical connections, is an obvious illustration of the potential complexity of dynamic networks of interactions. Another example is the so-called "Flash Crash" in the U.S. equity market: on May 6, 2010, a block sale of 4.1 billion dollars of futures contracts executed on behalf of a fund-management company triggered a complex pattern of interactions between the high-frequency algorithmic trading systems (algos) that buy and sell blocks of financial instruments and made the Dow Jones Industrial Average drop more

than 600 points, representing the disappearance of 800 billion dollars of market value. This example is an illustration of the faulty divergence of SoS behaviour, where the system starts to misbehave and dynamically creates new components that follow the same pattern and make the problem worse. Examples of this include when a SoS detects high energy use and invokes a new component to reduce the energy, thus consuming *more* energy. **Until now, such divergence has been mostly handled by humans that eventually observe the faulty behaviour and manually intervene to stop it. This human-based solution is not always successful and clearly unsatisfactory, since it acts retrospectively, when the system has already failed.**

3.1.2. Grand Challenge and Breakthroughs of ESTASYS

SoS are an efficient means of achieving high performance and are thus becoming ubiquitous. Society's increasing reliance on SoS demands that they are reliable, but tools to guarantee this at the design stage do not exist. Most conventional formal analysis techniques, even those dedicated to adaptive systems, fail when applied to SoS because they are designed to reason on systems whose state space can be predicted in advance. **The grand challenge addressed by ESTASYS is the fundamental overhaul of formal methods techniques in the design of SoS life cycle**.

It is clear that SMC can be applied to the verification of complex systems. Unfortunately, SMC cannot yet be applied to SoS, because existing techniques are designed to capture the behaviour of statically configured systems, or systems whose dynamical configuration arises from permutations of known components. ESTASYS defines new abstract computational models and extend the state of the art of SMC to include SoS.

ESTASYS proposes a new formal methodology to support an evolutionary adaptive and iterative SoS life-cycle. *We foresee the following breakthroughs:*

1. Our ground-breaking computational model addresses the complex dynamic nature of SoS. The model is based on new interface theories that take into account behaviours of possibly unknown components and thus abstract what is unknown.
2. Cutting edge algorithms coming from the area of statistics and learning are exploited to make predictions about autonomous systems making local decisions. For example, **statistical abstraction** abstracts the behaviour of unknown environments; interleaving analysis and runtime monitoring of deployed systems to continuously update distributions embedded in the interfaces.
3. New statistical algorithms for SMC that scale efficiently and handle undecidability impacts the formal analysis of complex systems.
4. Our results are implemented in a professional toolset, ESTASYS-PLASMA, that is constructed in close collaboration with our industrial partners. This ensures relevance to industry and potentially high impact in the marketplace.

3.1.3. Methodology and Organization

ESTASYS's main challenge is to lay the foundation of a novel rigorous software construction methodology for SoS, based on simulation, statistics and industrial practices. ESTASYS establishes theories and empirical evidence for the introduction of formal verification-based approaches in the rigorous design of SoS.

ESTASYS addresses essential research questions for the introduction of formal techniques to support the SoS life-cycle. SoS occur in multiple disciplines and therefore there is a need for a common language. In particular, notions such as **autonomous decisions and dynamicity** must be standardized and well understood by those that will apply our methodology. Additionally, **characterizing the topological structure** of a SoS is essential for the study of component interactions and data exchanges. The complexity of SoS requires the development of a **sound formal semantic foundation** to support deployment of formal methods. We thus identify a minimal computational model that characterize SoS, on which classes of properties of interest can be defined. The project investigates new simulation-based approaches, combined with other domains (statistics, learning, ...), to verify such properties on the new computational model. Finally, ESTASYS identifies under which conditions the new techniques can be used, to take decisions during design and evolution time, leading to a fully integrated development cycle.

ESTASYS focuses on both the static and dynamic properties of SoS. ESTASYS establishes models for each component and investigates the connection and dynamical interactions between them. ESTASYS's activities are organize in six main tasks: tasks 1, 2 and 3 are responsible for breakthrough 1; task 4 is responsible for breakthrough 2; task 5 is responsible for breakthrough 3; task 6 is responsible for breakthrough 4.

Task 1. Characterizing SoS. Examples of SoS found in various areas, such as health care, smart buildings and energy grids, are analysed and used to standardize notions of autonomous decisions and dynamicity. We also study and classify SoS-related problems, such as faulty behaviour divergence. Our objective is to derive in Task 2 formal models that abstract the above classification.

Task 2. Formal Modeling of SoS. Classical theories do not provide for SoS, hence we require new formal models for SoS that take into account (i) dynamicity and emergent behaviours, (ii) autonomous decisions of components, and (iii) architectural constraints, including information regarding the viability of the hardware. In particular, we devise new logics tailored to the specific needs of SoS. Such logics, dynamic by nature, includes extended notions of quantification, such as energy, and considers hardware constraints and distributions of system configurations. Task 2 includes modelling the various components running within the SoS and their (dynamical) interactions. This requires the definition of a new type of interface able to work with heterogeneous components and to abstract the behaviour of unknown resources. Interfaces act as an abstraction for the internal behaviour of each component and encodes the dynamical constraints of the SoS. They are used to (i) model and define the authorised interactions between the components, (ii) reason on dynamical aspects and (iii) abstract unknown behaviour.

Task 3. Statistical abstraction interleaving design and deployment. Abstraction techniques are necessary to reduce the complexity of SoS and to model uncertainty. Specifically, **statistical abstractions** of the observed runtime behaviour of components is used to quantify, e.g., the probability that a number of new components satisfying some constraints is started at a given execution point. Runtime verification monitors the executions of the deployed system to create distributions embedded in the interfaces developed in Task 1. When a deployed system is available, ESTASYS interleaves simulation, analysis and runtime monitoring, using real behaviour to update the statistical abstractions, and eventually replace some of those abstractions by concrete ESTASYS-Interface models. The ESTASYS methodology adopts a Bayesian approach: (i) an initial, plausible distribution is 'guessed', based on whatever is known; (ii) the system is simulated using the current approximated distribution; (iii) the behaviour of the simulated system becomes the new approximation; (iv) the process is iterated as necessary. While learning-based simulation approaches, such as model fitting, can be used to learn the abstraction by conducting simulations from a finite set of initial components, we have to provide clear evidence that a global property holds on the system if it holds on its corresponding statistical abstraction. The task requires strong competences in statistics.

Task 4. Developing Efficient Simulation and Monitoring Algorithms for SoS. The ground-breaking models developed in Task 2 requires efficient simulation and monitoring techniques. This necessitates the study of new algorithms for dynamically configured systems and monitoring approaches to reason on heterogeneous components and the new quantitative logics and interface paradigms developed in Task 2.
A major difficulty in developing monitoring techniques for SoS is that the components have their own goals and behave differently in different environments. Unnecessary high-level hypotheses on properties may drastically increase simulation time and should be avoided.

Task 5. Developing Efficient Statistical Techniques for SoS. SoS pose new challenges for statistical techniques, requiring the study of new SMC algorithms dedicated to SoS goals. In contrast to existing SMC algorithms that can only be applied to pure stochastic systems, SMC algorithms for SoS have to take into account the non-deterministic aspects of autonomous decisions made by neighbour components. We postulate that this can be done by extending very recent advances in reinforcement learning algorithms. Rare events play an important role in system reliability, so we include rare-event simulation algorithms, such as importance sampling and importance splitting, which can reduce variance and significantly increase simulation efficiency.

Task 6. Evaluating the impact of statistical and simulation-based techniques. Evidence of the success of ESTASYS is provided by the publishing of a complete experimental environment, ESTASYS-PLASMA, that supports the empirical validation of ESTASYS's theories. ESTASYS-PLASMA contains efficient implementations of the results discovered in Tasks 2-5, and will provide intuitive feedback mechanisms so that the engineer can use the results of the verification process to improve SoS design.

HYCOMES Team

3. Research Program

3.1. Hybrid Systems Modeling

Systems industries today make extensive use of mathematical modeling tools to design computer controlled physical systems. This class of tools addresses the modeling of physical systems with models that are simpler than usual scientific computing problems by using only Ordinary Differential Equations (ODE) and Difference Equations but not Partial Differential Equations (PDE). This family of tools first emerged in the 1980's with SystemBuild by MatrixX (now distributed by National Instruments) followed soon by Simulink by Mathworks, with an impressive subsequent development.

In the early 90's control scientists from the University of Lund (Sweden) realized that the above approach did not support component based modeling of physical systems with reuse [0]. For instance, it was not easy to draw an electrical or hydraulic circuit by assembling component models of the various devices. The development of the Omola language by Hilding Elmqvist was a first attempt to bridge this gap by supporting some form of Differential Algebraic Equations (DAE) in the models. Modelica quickly emerged from this first attempt and became in the 2000's a major international concerted effort with the Modelica Consortium [0]. A wider set of tools, both industrial and academic, now exists in this segment [0]. In the EDA sector, VHDL-AMS was developed as a standard [11].

Despite these tools are now widely used by a number of engineers, they raise a number of technical difficulties. The meaning of some programs, their mathematical semantics, can be tainted with uncertainty. A main source of difficulty lies in the failure to properly handle the discrete and the continuous parts of systems, and their interaction. How the propagation of mode changes and resets should be handled? How to avoid artifacts due to the use of a global ODE solver causing unwanted coupling between seemingly non interacting subsystems? Also, the mixed use of an equational style for the continuous dynamics with an imperative style for the mode changes and resets is a source of difficulty when handling parallel composition. It is therefore not uncommon that tools return complex warnings for programs with many different suggested hints for fixing them. Yet, these "pathological" programs can still be executed, if wanted so, giving surprising results — See for instance the Simulink examples in [6], [3] and [14].

Indeed this area suffers from the same difficulties that led to the development of the theory of synchronous languages as an effort to fix obscure compilation schemes for discrete time equation based languages in the 1980's. Our vision is that hybrid systems modeling tools deserve similar efforts in theory as synchronous languages did for the programming of embedded systems.

3.2. Background on non-standard analysis

Non-Standard analysis plays a central role in our research on hybrid systems modeling [3], [6], [15], [14]. The following text provides a brief summary of this theory and gives some hints on its usefulness in the context of hybrid systems modeling. This presentation is based on our paper [3], a chapter of Simon Bliudze's PhD thesis [21], and a recent presentation of non-standard analysis, not axiomatic in style, due to the mathematician Lindström [41].

[0] http://www.lccc.lth.se/media/LCCC2012/WorkshopSeptember/slides/Astrom.pdf
[0] https://www.modelica.org/
[0] SimScape by Mathworks, Amesim by LMS International, now Siemens PLM, and more.

Non-standard numbers allowed us to reconsider the semantics of hybrid systems and propose a radical alternative to the *super-dense time semantics* developed by Edward Lee and his team as part of the Ptolemy II project, where cascades of successive instants can occur in zero time by using $\mathbb{R}_+ \times \mathbb{N}$ as a time index. In the non-standard semantics, the time index is defined as a set $\mathbb{T} = \{n\partial \mid n \in {}^*\mathbb{N}\}$, where ∂ is an *infinitesimal* and ${}^*\mathbb{N}$ is the set of *non-standard integers*. Remark that 1/ $\mathbb{T}$ is dense in $\mathbb{R}_+$, making it "continuous", and 2/ every $t \in \mathbb{T}$ has a predecessor in $\mathbb{T}$ and a successor in $\mathbb{T}$, making it "discrete". Although it is not effective from a computability point of view, the *non-standard semantics* provides a framework that is familiar to the computer scientist and at the same time efficient as a symbolic abstraction. This makes it an excellent candidate for the development of provably correct compilation schemes and type systems for hybrid systems modeling languages.

Non-standard analysis was proposed by Abraham Robinson in the 1960s to allow the explicit manipulation of "infinitesimals" in analysis [48], [35], [10]. Robinson's approach is axiomatic; he proposes adding three new axioms to the basic Zermelo-Fraenkel (ZFC) framework. There has been much debate in the mathematical community as to whether it is worth considering non-standard analysis instead of staying with the traditional one. We do not enter this debate. The important thing for us is that non-standard analysis allows the use of the non-standard discretization of continuous dynamics "as if" it was operational.

Not surprisingly, such an idea is quite ancient. Iwasaki et al. [37] first proposed using non-standard analysis to discuss the nature of time in hybrid systems. Bliudze and Krob [22], [21] have also used non-standard analysis as a mathematical support for defining a system theory for hybrid systems. They discuss in detail the notion of "system" and investigate computability issues. The formalization they propose closely follows that of Turing machines, with a memory tape and a control mechanism.

The introduction to non-standard analysis in [21] is very pleasant and we take the liberty to borrow it. This presentation was originally due to Lindstrøm, see [41]. Its interest is that it does not require any fancy axiomatic material but only makes use of the axiom of choice — actually a weaker form of it. The proposed construction bears some resemblance to the construction of $\mathbb{R}$ as the set of equivalence classes of Cauchy sequences in $\mathbb{Q}$ modulo the equivalence relation $(u_n) \approx (v_n)$ iff $\lim_{n\to\infty}(u_n - v_n) = 0$.

3.2.1. Motivation and intuitive introduction

We begin with an intuitive introduction to the construction of the non-standard reals. The goal is to augment $\mathbb{R} \cup \{\pm\infty\}$ by adding, to each x in the set, a set of elements that are "infinitesimally close" to it. We will call the resulting set ${}^*\mathbb{R}$. Another requirement is that all operations and relations defined on $\mathbb{R}$ should extend to ${}^*\mathbb{R}$.

A first idea is to represent such additional numbers as convergent sequences of reals. For example, elements infinitesimally close to the real number zero are the sequences $u_n = 1/n$, $v_n = 1/\sqrt{n}$ and $w_n = 1/n^2$. Observe that the above three sequences can be ordered: $v_n > u_n > w_n > 0$ where 0 denotes the constant zero sequence. Of course, infinitely large elements (close to $+\infty$) can also be considered, e.g., sequences $x_u = n$, $y_n = \sqrt{n}$, and $z_n = n^2$.

Unfortunately, this way of defining ${}^*\mathbb{R}$ does not yield a total order since two sequences converging to zero cannot always be compared: if u_n and u'_n are two such sequences, the three sets $\{n \mid u_n > u'_n\}$, $\{n \mid u_n = u'_n\}$, and $\{n \mid u_n < u'_n\}$ may even all be infinitely large. The beautiful idea of Lindstrøm is to enforce that *exactly one of the above sets is important and the other two can be neglected*. This is achieved by fixing once and for all a finitely additive positive measure μ over the set $\mathbb{N}$ of integers with the following properties: [0]

1. $\mu : 2^{\mathbb{N}} \to \{0, 1\}$;
2. $\mu(X) = 0$ whenever X is finite;
3. $\mu(\mathbb{N}) = 1$.

[0] The existence of such a measure is non trivial and is explained later.

Now, once μ is fixed, one can compare any two sequences: for the above case, exactly one of the three sets must have μ-measure 1 and the others must have μ-measure 0. Thus, say that $u > u', u = u'$, or $u < u'$, if $\mu(\{n \mid u_n > u'_n\} = 1)$, $\mu(\{n \mid u_n = u'_n\}) = 1$, or $\mu(\{n \mid u_n < u'_n\}) = 1$, respectively. Indeed, the same trick works for many other relations and operations on non-standard real numbers, as we shall see. We now proceed with a more formal presentation.

3.2.2. Construction of non-standard domains

For I an arbitrary set, a *filter*$\mathcal{F}$ over I is a family of subsets of I such that:

1. the empty set does not belong to $\mathcal{F}$,
2. $P, Q \in \mathcal{F}$ implies $P \cap Q \in \mathcal{F}$, and
3. $P \in \mathcal{F}$ and $P \subset Q \subseteq I$ implies $Q \in \mathcal{F}$.

Consequently, $\mathcal{F}$ cannot contain both a set P and its complement P^c. A filter that contains one of the two for any subset $P \subseteq I$ is called an *ultra-filter*. At this point we recall Zorn's lemma, known to be equivalent to the axiom of choice:

Lemma 1 (Zorn's lemma) *Any partially ordered set $(X, \leq)$ such that any chain in X possesses an upper bound has a maximal element.*

A filter $\mathcal{F}$ over I is an ultra-filter if and only if it is maximal with respect to set inclusion. By Zorn's lemma, any filter $\mathcal{F}$ over I can be extended to an ultra-filter over I. Now, if I is infinite, the family of sets $\mathcal{F} = \{P \subseteq I \mid P^c \text{ is finite}\}$ is a *free* filter, meaning it contains no finite set. It can thus be extended to a free ultra-filter over I:

Lemma 2 Any infinite set has a free ultra-filter.

Every free ultra-filter $\mathcal{F}$ over I uniquely defines, by setting $\mu(P) = 1$ if $P \in \mathcal{F}$ and otherwise 0, a finitely additive measure [0]$\mu : 2^I \mapsto \{0, 1\}$, which satisfies

$$\mu(I) = 1 \text{ and, if } P \text{ is finite, then } \mu(P) = 0.$$

Now, fix an infinite set I and a finitely additive measure μ over I as above. Let $\mathbb{X}$ be a set and consider the Cartesian product $\mathbb{X}^I = (x_i)_{i \in I}$. Define $(x_i) \approx (x'_i)$ iff $\mu\{i \in I \mid x_i \neq x'_i\} = 0$. Relation $\approx$ is an equivalence relation whose equivalence classes are denoted by $[x_i]$ and we define:

$$^*\mathbb{X} = \mathbb{X}^I / \approx \tag{1}$$

$\mathbb{X}$ is naturally embedded into $^*\mathbb{X}$ by mapping every $x \in \mathbb{X}$ to the constant tuple such that $x_i = x$ for every $i \in I$. Any algebraic structure over $\mathbb{X}$ (group, ring, field) carries over to $^*\mathbb{X}$ by almost point-wise extension. In particular, if $[x_i] \neq 0$, meaning that $\mu\{i \mid x_i = 0\} = 0$ we can define its inverse $[x_i]^{-1}$ by taking $y_i = x_i^{-1}$ if $x_i \neq 0$ and $y_i = 0$ otherwise. This construction yields $\mu\{i \mid y_i x_i = 1\} = 1$, whence $[y_i][x_i] = 1$ in $^*\mathbb{X}$. The existence of an inverse for any non-zero element of a ring is indeed stated by the formula: $\forall x \, (x = 0 \vee \exists y \, (xy = 1))$. More generally:

Lemma 3 (Transfer Principle) Every first order formula is true over $^*\mathbb{X}$ iff it is true over $\mathbb{X}$.

The above general construction can simply be applied to $\mathbb{X} = \mathbb{R}$ and $I = \mathbb{N}$. The result is denoted $^*\mathbb{R}$; it is a field according to the transfer principle. By the same principle, $^*\mathbb{R}$ is totally ordered by $[u_n] \leq [v_n]$ iff $\mu\{n \mid u_n > v_n\} = 0$. We claim that, for any finite $[x_n] \in {}^*\mathbb{R}$, there exists a unique $st([x_n])$, call it the *standard part* of $[x_n]$, such that

$$st([x_n]) \in \mathbb{R} \text{ and } st([x_n]) \approx [x_n]\,. \tag{2}$$

[0]Observe that, as a consequence, μ cannot be sigma-additive (in contrast to probability measures or Radon measures) in that it is *not* true that $\mu(\bigcup_n A_n) = \sum_n \mu(A_n)$ holds for an infinite denumerable sequence A_n of pairwise disjoint subsets of $\mathbb{N}$.

To prove this, let $x = \sup\{u \in \mathbb{R} \mid [u] \leq [x_n]\}$, where $[u]$ denotes the constant sequence equal to u. Since $[x_n]$ is finite, x exists and we only need to show that $[x_n] - x$ is infinitesimal. If not, then there exists $y \in \mathbb{R}, y > 0$ such that $y < |x - [x_n]|$, that is, either $x < [x_n] - [y]$ or $x > [x_n] + [y]$, which both contradict the definition of x. The uniqueness of x is clear, thus we can define $st([x_n]) = x$. Infinite non-standard reals have no standard part in $\mathbb{R}$.

It is also of interest to apply the general construction (1) to $\mathbb{X} = I = \mathbb{N}$, which results in the set ${}^*\mathbb{N}$ of *non-standard natural numbers*. The non-standard set ${}^*\mathbb{N}$ differs from $\mathbb{N}$ by the addition of *infinite natural numbers*, which are equivalence classes of sequences of integers whose essential limit is $+\infty$.

3.3. Contract-Based Design, Interfaces Theories, and Requirements Engineering

System companies such as automotive and aeronautic companies are facing significant difficulties due to the exponentially raising complexity of their products coupled with increasingly tight demands on functionality, correctness, and time-to-market. The cost of being late to market or of imperfections in the products is staggering as witnessed by the recent recalls and delivery delays that many major car and airplane manufacturers had to bear in the recent years. The specific root causes of these design problems are complex and relate to a number of issues ranging from design processes and relationships with different departments of the same company and with suppliers, to incomplete requirement specification and testing.

We believe the most promising means to address the challenges in systems engineering is to employ structured and formal design methodologies that seamlessly and coherently combine the various viewpoints of the design space (behavior, space, time, energy, reliability, ...), that provide the appropriate abstractions to manage the inherent complexity, and that can provide correct-by-construction implementations. The following technology issues must be addressed when developing new approaches to the design of complex systems:

- The overall design flows for heterogeneous systems and the associated use of models across traditional boundaries are not well developed and understood. Relationships between different teams inside a same company, or between different stake-holders in the supplier chain, are not well supported by solid technical descriptions for the mutual obligations.
- System requirements capture and analysis is in large part a heuristic process, where the informal text and natural language-based techniques in use today are facing significant challenges. Formal requirements engineering is in its infancy: mathematical models, formal analysis techniques and links to system implementation must be developed.
- Dealing with variability, uncertainty, and life-cycle issues, such as extensibility of a product family, are not well-addressed using available systems engineering methodologies and tools.

The challenge is to address the entire process and not to consider only local solutions of methodology, tools, and models that ease part of the design.

Contract-based design has been proposed as a new approach to the system design problem that is rigorous and effective in dealing with the problems and challenges described before, and that, at the same time, does not require a radical change in the way industrial designers carry out their task as it cuts across design flows of different type. Indeed, contracts can be used almost everywhere and at nearly all stages of system design, from early requirements capture, to embedded computing infrastructure and detailed design involving circuits and other hardware. Contracts explicitly handle pairs of properties, respectively representing the assumptions on the environment and the guarantees of the system under these assumptions. Intuitively, a contract is a pair $C = (A, G)$ of assumptions and guarantees characterizing in a formal way 1) under which context the design is assumed to operate, and 2) what its obligations are. Assume/Guarantee reasoning has been known for a long time, and has been used mostly as verification mean for the design of software [45]. However, contract based design with explicit assumptions is a philosophy that should be followed all along the design, with all kinds of models, whenever necessary. Here, specifications are not limited to profiles, types, or taxonomy of data, but also describe the functions, performances of various kinds (time and energy), and reliability. This amounts to enrich a component's interface with, on one hand, formal specifications of the behavior of the environment in

which the component may be instantiated and, on the other hand, of the expected behavior of the component itself. The consideration of rich interfaces is still in its infancy. So far, academic researchers have addressed the mathematics and algorithmics of interfaces theories and contract-based reasoning. To make them a technique of choice for system engineers, we must develop:

- Mathematical foundations for interfaces and requirements engineering that enable the design of frameworks and tools;
- A system engineering framework and associated methodologies and tool sets that focus on system requirements modeling, contract specification, and verification at multiple abstraction layers.

A detailed bibliography on contract and interface theories for embedded system design can be found in [4]. In a nutshell, contract and interface theories fall into two main categories:

Assume/guarantee contracts. By explicitly relying on the notions of assumptions and guarantees, A/G-contracts are intuitive, which makes them appealing for the engineer. In A/G-contracts, assumptions and guarantees are just properties regarding the behavior of a component and of its environment. The typical case is when these properties are formal languages or sets of traces, which includes the class of safety properties [38], [29], [44], [13], [30]. Contract theories were initially developed as specification formalisms able to refuse some inputs from the environment [36]. A/G-contracts were advocated by the SPEEDS project [16]. They were further experimented in the framework of the CESAR project [31], with the additional consideration of *weak* and *strong* assumptions. This is still a very active research topic, with several recent contributions dealing with the timed [20] and probabilistic [25], [26] viewpoints in system design, and even mixed-analog circuit design [46].

Automata theoretic interfaces. Interfaces combine assumptions and guarantees in a single, automata theoretic specification. Most interface theories are based on Lynch Input/Output Automata [43], [42]. Interface Automata [51], [50], [52], [27] focus primarily on parallel composition and compatibility: Two interfaces can be composed and are compatible if there is at least one environment where they can work together. The idea is that the resulting composition exposes as an interface the needed information to ensure that incompatible pairs of states cannot be reached. This can be achieved by using the possibility, for an Interface Automaton, to refuse selected inputs from the environment in a given state, which amounts to the implicit assumption that the environment will never produce any of the refused inputs, when the interface is in this state. Modal Interfaces [5] inherit from both Interface Automata and the originally unrelated notion of Modal Transition System [40], [12], [23], [39]. Modal Interfaces are strictly more expressive than Interface Automata by decoupling the I/O orientation of an event and its deontic modalities (mandatory, allowed or forbidden). Informally, a *must* transition is available in every component that realizes the modal interface, while a *may* transition needs not be. Research on interface theories is still very active. For instance, timed [53], [17], [19], [33], [32], [18], probabilistic [25], [34] and energy-aware [28] interface theories have been proposed recently.

Requirements Engineering is one of the major concerns in large systems industries today, particularly so in sectors where certification prevails [49]. DOORS projects collecting requirements are poorly structured and cannot be considered a formal modeling framework today. They are nothing more than an informal documentation enriched with hyperlinks. As examples, medium size sub-systems may have a few thousands requirements and the Rafale fighter aircraft has above 250,000 of them. For the Boeing 787, requirements were not stable while subcontractors performed the development of the fly-by-wire and of the landing gear subsystems.

We see Contract-Based Design and Interfaces Theories as innovative tools in support of Requirements Engineering. The Software Engineering community has extensively covered several aspects of Requirements Engineering, in particular:

- the development and use of large and rich *ontologies*; and
- the use of Model Driven Engineering technology for the structural aspects of requirements and resulting hyperlinks (to tests, documentation, PLM, architecture, and so on).

Behavioral models and properties, however, are not properly encompassed by the above approaches. This is the cause of a remaining gap between this phase of systems design and later phases where formal model based methods involving behavior have become prevalent—see the success of Matlab/Simulink/Scade technologies. We believe that our work on contract based design and interface theories is best suited to bridge this gap.

SUMO Project-Team

3. Research Program

3.1. Model expressivity and quantitative verification

The overall objective of this axis is to combine the quantitative aspects of models with a distributed/modular setting, while maintaining the tractability of verification and management objectives.

There is first an issue of modeling, to nicely weave time, costs and probabilities with concurrency and/or asynchronism. Several approaches are quite natural, as time(d) Petri nets, networks of timed automata, communicating synchronously or through FIFO, etc. But numerous bottlenecks remain. For example, so far, no probabilistic model nicely fits the notion of concurrency: there is no clean way to express that two components are stochastically independent between two rendez-vous.

Second, the models we want to manipulate should allow for quantitative verification. This covers two aspects: either the verification question is itself quantitative (compute an optimal scheduling policy) or boolean (decide whether the probability is greater than a threshold). Our goal is to explore the frontier between decidable and undecidable problems, or more pragmatically tractable and untractable problems. Of course, there is a tradeoff between the expressivity and the tractability of a model. Models that incorporate distributed aspects, probabilities, time, etc, are typically untractable. In such a case, abstraction or approximation techniques are a work around that we will explore.

In more details, our research program on this axis covers the following topics:

- the verification of distributed timed systems,
- the verification of large scale probabilistic (dynamic) systems, with a focus on approximation techniques for such systems,
- the evaluation of the opacity/diagnosability degree of stochastic systems,
- the design of modular testing methods for large scale modular systems.

3.2. Management of large distributed systems

The generic terms of "supervision" or "management" of distributed systems cover problems like control (and controller synthesis), diagnosis, sensor placement, planning, optimization, (state) estimation, parameter identification, testing, etc. These questions have both an offline and an online facet. The literature is abundant for discrete event systems (DES), even in the distributed case, and for some quantitative aspects of DES in the centralized case (for example partially observed Markov decision processes (POMDP), probabilistic diagnosis/diagnosers, (max,+) approaches to timed automata). And there is a strong trend driving formal methods approaches towards quantitative models and questions like the most likely diagnosis, control for best average reward or for best QoS, optimal sensor placement, computing the probability of failure (un)detection, estimating the average impact of some failure or of a decision, etc. This second research axis focuses on these issues, and aims at developing new concepts and tools to master some already existing large scale systems, as telecommunication networks, cloud infrastructures, web-services, etc. (see the Application Domains section).

The objective being to address large systems, our work will be driven by two considerations: how to take advantage of the modularity of systems, and how to best approximate/abstract too complex systems by more tractable ones. We mention below main topics we will focus on:

- Approximate management methods. We will explore the relevance of ideas developed for large scale stochastic systems, as turbo-algorithms for example, in the setting of modular dynamic systems.
- Self-modeling, which consists in managing large scale systems that are known by their building rules, but which specific managed instance is only discovered at runtime, and on the fly. The model of the managed system is built on-line, following the needs of the management algorithms.

- Distributed control. We will tackle issues related to asynchronous communications between local controllers, and abstraction techniques to address large systems.
- Test and enforcement. We will tackle coverage issues for the test of large systems, and the test and enforcement of properties for timed models, or for systems handling data.

3.3. Data driven systems

The term data-driven systems refers to systems the behavior of which depends both on explicit workflows (scheduling and durations of tasks, calls to possibly distant services,...) and on the data processed by the system (stored data, parameters of a request, results of a request,...). This family of systems covers workflows that convey data (business processes or information systems), transactional systems (web stores), large databases managed with rules (banking systems), collaborative environments (health systems), etc. These systems are distributed, modular, and open: they integrate components and sub-services distributed over the web and accept requests from clients. Our objective is to provide validation and supervision tools for such systems. To achieve this goal, we have to solve several challenging tasks:

- provide realistic models, and sound automated abstraction techniques, to reason on models that are reasonable abstractions of real implemented systems designed in low-level languages (for instance BPEL (Business Process Execution Language)). These models should be able to encompass modularity, distribution, in a context where workflows and data aspects are tightly connected.
- provide tractable solutions for validation of models. Important questions that are frequently addressed (for instance safety properties or coverability) should remain decidable on our models, but also with a decent complexity.
- address design of data driven systems in a declarative way: declarative models are another way to handle data-driven systems. Rather than defining the explicit workflows and their effects on data, rule-based models state how actions are enacted in terms of the shape (pattern matching) or value of the current data. Such declarative models are well accepted in business processes (Companies such as IBM use their own model of business rules [53] to interact with their clients). Our approach is to design collaborative activities in terms of distributed structured documents, that can be seen as communicating rewriting systems. This modeling paradigm also includes models such as distributed Active XML [48], [51]. We think that distributed rewriting rules or attributed grammars can provide a practical but yet formal framework for maintenance, by providing a solution to update mandatory documentation during the lifetime of an artifact.
- address QoS management in large reconfigurable systems:

Data driven distributed systems such as web services often have constraints in terms of QoS. This calls for an analysis of quantitative features, and for reconfiguration techniques to meet QoS contracts. We will build from the experience in our team on QoS contracts composition [54] and planning [47], [49] to propose optimization and reconfiguration schemes.

TASC Project-Team

3. Research Program

3.1. Overview

Basic research is guided by the challenges raised before: to classify and enrich the models, to automate reformulation and resolution, to dissociate declarative and procedural knowledge, to come up with theories and tools that can handle problems involving both continuous and discrete variables, to develop modelling tools and to come up with solving tools that scale well. On the one hand, **classification aspects** of this research are integrated within a knowledge base about combinatorial problem solving: the global constraint catalog (see http://sofdem.github.io/gccat/). On the other hand, **solving aspects** are capitalized within the constraint solving system CHOCO. Lastly, within the framework of its activities of valorisation, teaching and of partnership research, the team uses constraint programming for solving various concrete problems. The challenge is, on one side to increase the visibility of the constraints in the others disciplines of computer science, and on the other side to contribute to a broader diffusion of the constraint programming in the industry.

3.2. Fundamental Research Topics

This part presents the research topics investigated by the project:

- Global Constraints Classification, Reformulation and Filtering,
- Convergence between Discrete and Continuous,
- Dynamic, Interactive and over Constrained Problems,
- Solvers.

These research topics are in fact not independent. The work of the team thus frequently relates transverse aspects such as explained global constraints, Benders decomposition and explanations, flexible and dynamic constraints, linear models and relaxations of constraints.

3.2.1. Constraints Classification, Reformulation and Filtering

In this context our research is focused (a) first on identifying recurring combinatorial structures that can be used for modelling a large variety of optimization problems, and (b) exploit these combinatorial structures in order to come up with efficient algorithms in the different fields of optimization technology. The key idea for achieving point (b) is that many filtering algorithms both in the context of Constraint Programming, Mathematical Programming and Local Search can be interpreted as the maintenance of invariants on specific domains (e.g., graph, geometry). The systematic classification of global constraints and of their relaxation brings a synthetic view of the field. It establishes links between the properties of the concepts used to describe constraints and the properties of the constraints themselves. Together with SICS, the team develops and maintains *a catalog of global constraints*, which describes the semantics of more than 431 constraints, and proposes a unified mathematical model for expressing them. This model is based on graphs, automata and logic formulae and allows to derive filtering methods and automatic reformulation for each constraint in a unified way (see http://www.emn.fr/x-info/sdemasse/gccat/index.html). We consider hybrid methods (i.e., methods that involve more than one optimization technology such as constraint programming, mathematical programming or local search), to draw benefit from the respective advantages of the combined approaches. More fundamentally, the study of hybrid methods makes it possible to compare and connect strategies of resolution specific to each approach for then conceiving new strategies. Beside the works on classical, complete resolution techniques, we also investigate local search techniques from a mathematical point of view. These partly random algorithms have been proven very efficient in practice, although we have little theoretical knowledge on their behaviour, which often makes them problem-specific. Our research in that area is focused on a probabilistic model of local search techniques, from which we want to derive quantified information on their behaviour, in order to

use this information directly when designing the algorithms and exploit their performances better. We also consider algorithms that maintain local and global consistencies, for more specific models. Having in mind the trade off between genericity and effectiveness, the effort is put on the efficiency of the algorithms with guarantee on the produced levels of filtering. This effort results in adapting existing techniques of resolution such as graph algorithms. For this purpose we identify necessary conditions of feasibility that can be evaluated by efficient incremental algorithms. Genericity is not neglected in these approaches: on the one hand the constraints we focus on are applicable in many contexts (for example, graph partitioning constraints can be used both in logistics and in phylogeny); on the other hand, this work led to study the portability of such constraints and their independence with specific solvers. This research orientation gathers various work such as strong local consistencies, graph partitioning constraints, geometrical constraints, and optimization and soft constraints. Within the perspective to deal with complex industrial problems, we currently develop meta constraints (e.g. *geost*) handling all together the issues of large-scale problems, dynamic constraints, combination of spatial and temporal dimensions, expression of business rules described with first order logic.

3.2.2. Convergence between Discrete and Continuous

Many industrial problems mix continuous and discrete aspects that respectively correspond to physical (e.g., the position, the speed of an object) and logical (e.g., the identifier, the nature of an object) elements. Typical examples of problems are for instance:

- *Geometrical placement problems* where one has to place in space a set of objects subject to various geometrical constraints (i.e., non-overlapping, distance). In this context, even if the positions of the objects are continuous, the structure of optimal configurations has a discrete nature.
- *Trajectory and mission planning problems* where one has to plan and synchronize the moves of several teams in order to achieve some common goal (i.e., fire fighting, coordination of search in the context of rescue missions, surveillance missions of restricted or large areas).
- *Localization problems in mobile robotic* where a robot has to plan alone (only with its own sensors) its trajectory. This kind of problematic occurs in situations where the GPS cannot be used (e.g., under water or Mars exploration) or when it is not precise enough (e.g., indoor surveillance, observation of contaminated sites).

Beside numerical constraints that mix continuous and integer variables we also have global constraints that involve both type of variables. They typically correspond to graph problems (i.e., graph colouring, domination in a graph) where a graph is dynamically constructed with respect to geometrical and-or temporal constraints. In this context, the key challenge is avoiding decomposing the problem in a discrete and continuous parts as it is traditionally the case. As an illustrative example consider *the wireless network deployment problem*. On the one hand, the continuous part consists of finding out where to place a set of antenna subject to various geometrical constraints. On the other hand, by building an interference graph from the positions of the antenna, the discrete part consists of allocating frequencies to antenna in order to avoid interference. In the context of convergence between discrete and continuous variables, our goals are:

- First to identify and compare typical class of techniques that are used in the context of continuous and discrete solvers.
- To see how one can unify and/or generalize these techniques in order to handle in an integrated way continuous and discrete constraints within the same framework.

3.2.3. Dynamic, Interactive and over Constrained Problems

Some industrial applications are defined by a set of constraints which may change over time, for instance due to an interaction with the user. Many other industrial applications are over-constrained, that is, they are defined by set of constraints which are more or less important and cannot be all satisfied at the same time. Generic, dedicated and explanation-based techniques can be used to deal efficiently with such applications. Especially, these applications rely on the notion of *soft constraints* that are allowed to be (partially) violated. The generic concept that captures a wide variety of soft constraints is the violation measure, which is coupled with specific resolution techniques. Lastly, soft constraints allow to combine the expressive power of global constraints with local search frameworks.

3.2.4. Solvers

- *Discrete solver* Our theoretical work is systematically validated by concrete experimentations. We have in particular for that purpose the CHOCO constraint platform. The team develops and maintains CHOCO initially with the assistance of the laboratory e-lab of Bouygues (G. Rochart), the company Amadeus (F. Laburthe), and others researchers such as H. Cambazard (4C, INP Grenoble). Since 2008 the main developments are done by Charles Prud'homme and Xavier Lorca. The functionalities of CHOCO are gradually extended with the outcomes of our works: design of constraints, analysis and visualization of explanations, etc. The open source CHOCO library is downloaded on average 450 times each month since 2006. CHOCO is developed in line with the research direction of the team, in an open-minded scientific spirit. Contrarily to other solvers where the efficiency often relies on problem-specific algorithms, CHOCO aims at providing the users both with reusable techniques (based on an up-to-date implementation of the global constraint catalogue) and with a variety of tools to ease the use of these techniques (clear separation between model and resolution, event-based solver, management of the over-constrained problems, explanations, etc.).
- *Continuous solver* Since 2009 year, due to the hiring of Gilles Chabert, the team is also involved in the development of the continuous constraint solver IBEX. These developments led us to new research topics, suitable for the implementation of discrete and continuous constraint solving systems: portability of the constraints, management of explanations, incrementality and recalculation. They partially use aspect programming (in collaboration with the InriaASCOLA team).
- *Constraint programming and verification* Constraint Programming has already had several applications to verification problems. It also has many common ideas with Abstract Interpretation, a theory of approximation of the semantics of programs. In both cases, we are interested in a particular set (solutions in CP, program traces in semantics), which is hard or impossible to compute, and this set is replaced by an over-approximation (consistent domains / abstract domains). Previous works (internship of Julie Laniau, PhD of Marie Pelleau, collaboration with the Abstract Interpretation team at the ENS and Antoine Miné in particular) have exhibited some of these links, and identified some situations where the two fields, Abstract Interpretation and Constraint Programming, can complement each other. It is the case in real-time stream processing languages, where Abstract Interpretation techniques may not be precise enough when analyzing loops. With the PhD of Anicet Bart, we are currently working on using CP techniques to find loop invariants for the Faust language, a functional sound processing language.

This work around the design and the development of solvers thus forms the fourth direction of basic research of the project.

TEA Project-Team

3. Research Program

3.1. State of the Art

System design based on the “synchronous paradigm” has focused the attention of many academic and industrial actors on abstracting non-functional implementation details from system design. This design abstraction focuses on the logic of interaction in reactive programs rather than their timed behaviour, allowing to secure functional correctness while remaining an intuitive programming model for embedded systems.

Maintaining the “synchronous hypothesis” on software at runtime, however, demands a quasi-synchronous model of execution (hardware or middleware) in order to be effectively implemented [0]. Strong software constraints to ensure functional correctness imply strong runtime restrictions and simple hardware. If we look at recent features found in synchronous programming languages such as Quartz [0], Lucid [0] departing from the simpler semantics of Esterel [0] and Lustre [0], we observe that all try to cope in a way or another with the availability of more general execution architectures: clock domains [0], pipelining [0], streaming [0]. Unfortunately, attempts to scale the simple "typed programming language" approach of the 90’s [0] to the above purpose hit inherent computational complexity limits. For example, a periodic clock operation like $0^{(1920*(1080-480))}\{0^{1200}1^{720}\}^{480}$ in Lucy-n (0^n means n zeros) yields an exponentially larger term [0]. This explains why team TEA opts for focusing on the semantics of time and concurrency in system design and on implementing the implied design methodologies using program analysis and abstract interpretation.

By contrast with a synchronous hypothesis, the polychronous MoCC implemented in the specification language Signal, available in the Eclipse project POP [0] and in the CCSL standard [0], is inherently capable of describing circuits and systems with multiple clocks.

The Eclipse project POP provides a tooled infrastructure to refine high-level specifications into real-time streaming applications or locally synchronous and globally asynchronous systems, through a series of model analysis and synthesis libraries. These tool-supported refinement and transformation techniques can assist the system engineer from the earliest design stages of requirement specification to the latest stages of synthesis, scheduling and deployment. These characteristics make polychrony much closer to the required semantic for compositional, refinement-based, architecture-driven, system design.

3.2. Modelling Time

The elegant abstraction offered by the "synchronous hypothesis" [0] has translated in famous leitmotivs like *"computation takes no time"* and *"communication is instantaneous"* and contributed to the impact and commercial success of Esterel Studio [0] and SCADE [0].

[0] *A protocol for loosely time-triggered architectures*. A. Benveniste et al. Embedded Software Conference. ACM, 2002
[0] The Averest System http://www.averest.org.
[0] Lucid synchrone http://www.di.ens.fr/~pouzet/lucid-synchrone.
[0] *The Esterel synchronous programming language*. G. Berry, G. Gonthier. Science of Computer Programming, v. 19(2). Elsevier, 1992.
[0] *The synchronous data flow programming language Lustre*. Halbwachs, N., Caspi, P., Raymond, P., Pilaud, D. Proceedings of the IEEE v. 79(9), 1991.
[0] *A formal semantics of clock refinement in imperative synchronous languages*. Gemünde, M., Brandt, J., Schneider, K. Application of Concurrency to System Design. IEEE Press, 2010.
[0] *Parallelism with futures in Lustre*. Cohen, A., Gérard, L., Pouzet, M. Embedded Software Conference. ACM, 2012.
[0] *N-synchronous Kahn networks*. Cohen, A., et al. Principles of Programming Languages. ACM, 2006.
[0] A. Benveniste et al. *The Synchronous Languages Twelve Years Later*. Proceedings of the IEEE v. 91(1), 2003.
[0] http://www.di.ens.fr/~guatto/slides_parkas_14_05_12.pdf, page 15.
[0] *Polychrony on POLARSYS (POP)*, an Eclipse project in the POLARSYS Industry Working Group, 2013. https://www.POLARSYS.org/projects/POLARSYS.pop
[0] *Clock Constraints in UML/MARTE CCSL*. C. André, F. Mallet. Technical Report RR-6540. Inria, 2008. http://hal.inria.fr/inria-00280941
[0] *The synchronous languages 12 years later*. A. Benveniste, et al. Proceedings of IEEE, 91(1), 2003.
[0] *Esterel Studio*, Sinfora. http://www.synfora.com/products/esterelStudio.html.

Meanwhile, proposals and standards have appeared to push the technical boundaries of synchronous concurrency, in order to address a larger spectrum of concerns related to modern, heterogeneous, many-core architectures. The challenge becomes more largely about representing time in system design, alongside with many, so called, non-functional properties: cost, power, heat, speed, throughput.

One reference for the purpose of modelling timed hardware behaviour is PSL [0]. PSL is a formal specification language based on Kleene algebras that was originally designed to model regular hardware signal traces. The duality between automata and this formalism also makes it suitable to express requirements, formal properties and abstraction of program behaviours. It is widely used for modelling and verification of hardware systems.

A more recent reference of broader spectrum is CCSL [0], the clock constraints specification language of UML Marte. CCSL's core specification formalism is based on the Signal MoCC, it is synchronous and multi-clocked. Yet, CCSL supports extensions to model multi-rate, multi-periodic systems, that are adequate to represent hardware clocks, as well as asynchronous and continuous extensions (although largely unexploited in the related work). Another well-developed model is that of Ptolemy [0], which represents time as a first-class citizen alongside data carried by streams in the modelled system. It relates to the notion of PRET [0], (precision time machine) to support real-time simulation.

In the meantime, and from a totally different perspective, type theory has made considerable advances since the avent of effect systems [0] to formally represent formal properties alongside with values. Hybrid types [0] (linked to interface and contract theories), refinement types [0], value-dependant types, allow formal program properties, logical or temporal, to flow alongside with data-types during program analysis and verification. While a combination of all the above is yet unexplored, it offers an exciting venue for contributing in either/both of these fields with new theoretical developments on modelling time using principles of type theory.

3.3. Modelling Architectures

An architectural model represents components in a distributed system as boxes with well-defined interfaces, connections between ports on component interfaces, and specifies component properties that can be used in analytical reasoning about the model. Models are hierarchically organised, so that each box can contain another system with its own set of boxes and connections between them. An architecture description language for embedded systems, for which timing and resource availability form an important part of the requirements, must in addition describe resources of the system platform, such as processors, memories, communication links, etc. Several architectural modelling languages for embedded systems have emerged in recent years, including the SAE AADL [0], SysML [0], UML MARTE [0].

An architectural specification serves several important purposes. First, it breaks down a system model into manageable components to establish clear interfaces between components. In this way, complexity becomes manageable by hiding details that are not relevant at a given level of abstraction. Clear, formally defined, component interfaces allow us to avoid integration problems at the implementation phase. Connections between components, which specify how components affect each other, help propagate the effects of a change in one component to the linked components.

[0] *Scade System*, ANSYS. http://www.esterel-technologies.com/products/scade-system
[0] *IEEE Standard for Property Specification Language*. IEEE, 2005. http://dx.doi.org/10.1109/IEEESTD.2005.97780.
[0] *CCSL: specifying clock constraints with UML/MARTE*, OMG, 2008. http://www.omgmarte.org/node/66.
[0] *Ptolemy*, UC Berkeley. http://ptolemy.eecs.berkeley.edu.
[0] *Precision Timed Computation in Cyber-Physical Systems*. E. A. Lee and S. A. Edwards, 2007. http://ptolemy.eecs.berkeley.edu/publications/papers/07/PRET.
[0] *Polymorphic effect systems*. J. M. Lucassen , D. K. Gifford. Principles of Programming Languages. ACM, 1988.
[0] *Hybrid type checking*. K.W. Knowles and C. Flanagan. ACM Transactions on Programming languages and systems, 32(2). ACM, 2010
[0] *Abstract Refinement Types*. N. Vazou, P. Rondon, and R. Jhala. European Symposium on Programming. Springer, 2013.
[0] *Architecture Analysis and Design Language*, AS-5506. SAE, 2004. http://standards.sae.org/as5506b
[0] *System Modelling Language*. OMG, 2007. http://www.omg.org/spec/SysML
[0] *UML Profile for MARTE*. OMG, 2009. http://www.omg.org/spec/MARTE

Most importantly, an architectural model is a repository to share knowledge about the system being designed. This knowledge can be represented as requirements, design artefacts, component implementations, held together by a structural backbone. Such a repository enables automatic generation of analytical models for different aspects of the system, such as timing, reliability, security, performance, energy, etc. Since all the models are generated from the same source, the consistency of assumptions w.r.t. guarantees, of abstractions w.r.t. refinements, used for different analyses becomes easier, and can be properly ensured in a design methodology based on formal verification and synthesis methods.

Related works in this aim, and closer in spirit to our approach (to focus on modelling time) are domain-specific languages such as Prelude [0] to model the real-time characteristics of embedded software architectures. Conversely, standard architecture description languages could be based on algebraic modelling tools, such as interface theories with the ECDAR tool [0].

3.4. Time Scheduling

Cyber-physical systems are reactive systems whose correctness not only depends on a deterministic behavior but also on timing predictability. The timing parameters of a CPS are requirements that arise from the system's specification (e.g. minimum throughput, maximum latency, deadlines) or timing properties of the physical and cyber-parts that restrict the CPS implementation. The design of a CPS must ensure that these timing requirements will be met, even in the worst-case scenario, through the different components and their timing properties.

3.4.1. Scheduling theory

Real-time scheduling theory provides tools for predicting the timing behaviour of a CPS which consists of many interacting software and hardware components. Expressing parallelism among software components is a crucial aspect of the design process of a CPS. It allows for efficient partition and exploitation of available resources. In the real-time scheduling theory literature, many models of computation have been proposed to express such parallelism, for instance:

- Set of independent periodic, sporadic, or aperiodic tasks where each real-time task is generally characterised with some timing parameters: deadline, period, first start time, jitter, etc. The periodic and sporadic task models [0] are very well studied task models since they allow to analytically reason about the timing behaviour of tasks. More expressive task models [0] such as the multi-frame and the recurring real-time task models have also emerged.
- Task graph models [0] where precedence constraints among real-time tasks may exist.
- Data-flow graph models such as synchronous data-flow (SDF [0]) and cyclo-static dataflow (CSDF [0]. IEEE, 1996.) models where the set of tasks (also called actors) communicate with each other through FIFO channels. When it fires, an actor consumes a predefined number of tokens from its inputs and produces a predefined number of tokens on its outputs. The scheduling problem is hence more complex since data dependencies must be satisfied.

[0] *The Prelude language*. LIFL and ONERA, 2012. http://www.lifl.fr/~forget/prelude.html
[0] *PyECDAR, timed games for timed specifications*. Inria, 2013. https://project.inria.fr/pyecdar
[0] *Scheduling algorithms for multiprogramming in a hard-real-time environment*. C. L. Liu and J. W. Layland. Journal of the ACM 20(1), 1973.
[0] *The digraph real-time task model*. M. Stigge, P. Ekberg, N. Guan, and W. Yi. Real-Time and Embedded Technology and Applications Symposium. IEEE, 2011.
[0] *Task graph scheduling using timed automata*. Y. Abdeddaïm, A. Kerbaa, and O. Maler. International Symposium on Parallel and Distributed Processing. IEEE, 2003.
[0] *Synchronous data-flow*. E. A. Lee and D. G. Messerschmitt. Proceedings of the IEEE, 1987.
[0] *Cycle-static dataflow*. G. Blisen, M. Engels, R. Lauwereins, and J. Peperstraete. Transactions on Signal Processing

The literature about real-time scheduling of sets of independent real-time tasks [0] provides very mature schedulability tests regarding many scheduling strategies, preemptive or non-preemptive scheduling, uniprocessor or multiprocessor scheduling, etc. Historically, real-time systems where scheduled by cyclic executives (i.e. static scheduling). However, since this approach produces rigid and difficult to maintain systems and handles only periodic tasks, the research community has proposed many dynamic scheduling algorithms, which can be classified as fixed-priority scheduling (e.g. rate-monotonic scheduling, deadline monotonic scheduling) and dynamic priority scheduling (e.g. earliest-deadline first scheduling, least laxity scheduling). Multiprocessor scheduling can be further classified as partitioned scheduling (each task is allocated to a processor and no migration is allowed), global scheduling (a single job can migrate to and execute on different processors), or hybrid.

Scheduling of data-flow graphs has also been extensively studied in the past decades. Static-periodic scheduling is the main scheduling approach, which consists in infinitely repeating a firing sequence of actors. This problem has been addressed with respect to many performance criteria: throughput maximisation [0], latency minimisation [0], buffer minimisation [0], code size minimisation [0], etc. Recently, real-time dynamic scheduling (fixed-priority and earliest-deadline first scheduling) of data-flow graphs has been addressed where actors are mapped to periodic real-time tasks and existing schedulability tests are adapted to synthesise the timing characteristics of actors [00]

3.5. Virtual Prototyping

Virtual Prototyping is the technology of developing realistic simulators from models of a system under design; that is, an emulated device that captures most, if not all, of the required properties of the real system, based on its specifications. A virtual prototype should be run and tested like the real device. Ideally, the real application software would be run on the virtual prototyping platform and produce the same results as the real device with the same sequence of outputs and reported performance measurements. This may be true to some extent only. Some trade-offs have often to be made between the accuracy of the virtual prototype, and time to develop accurate models.

A virtual prototyping platform must include operating system or hardware emulation technology since the hardware functions must be simulated at least to a minimum extent in order to run the software and evaluate the design alternatives. The hardware simulation engine is a key component of a virtual prototyping platform, which makes it possible to run the application software and produce output that can be analysed by other tools. Because electronic design tools (EDAs) simulate the hardware in every detail, it is possible to verify that the circuit operates properly and also to measure how many clock cycles will be required to achieve an operation. But because they simulate very low-level operations, simulation is much too slow to be usable for virtual prototyping. The authors of the FAST system [0] and SocLib project reports [0] speed-ups with a factor of several

[0] *A survey of hard real-time scheduling for multiprocessor systems*. R. I. Davis and A. Burns. *ACM Computing Survey* 43(4), 2011.

[0] *Throughput analysis of synchronous data-flow graphs*. Ghamarian, A.H. et al. Application of Concurrency to System Design. IEEE, 2006

[0] *Latency minimization for synchronous data flow graphs*. A. H. Ghamarian, et al. Conference on Digital System Design Architectures, Methods and Tools. Euromicro, 2007.

[0] *Minimal memory schedules for data-flow networks*. M. Cubric and P. Panangaden. International Conference on Concurrency Theory. Springer, 1993.

[0] *Looped schedules for dataflow descriptions of multirate signal processing algorithms*. S. S. Bhattacharyya and E. A. Lee. Journal of Formal Methods in System Design. Kluwer, 1994.

[0] *Affine data-flow graphs for the synthesis of hard real-time applications*. A. Bouakaz, J.-P. Talpin, and J. Vitek. International Conference on Application of Concurrency to System Design. IEEE Press, 2012.

[0] *Hard-real-time scheduling of data-dependent tasks in embedded streaming applications*. M. Bamakhrama and T. Stefanov. International Conference on Embedded Software. ACM, 2011.

[0] *The fast methodology for high-speed SOC simulation.* D. Chiou, et al. International conference on Computer-aided design. IEEE, 2007.

[0] *Using binary translation in event driven simulation for fast and flexible MPSOC simulation.* M. Gligor, N. Fournel, and F. Pétrot. In CODES+ISSS, IEEE, 2009.

hundreds in a comparison between their cycle accurate simulator and their virtual prototyping framework. A factor of the order of 100 times faster than EDA tools is required for virtual prototyping.

In order to speed-up simulation time, the virtual prototype must trade-off with something. Depending upon the application designers goals, one may be interested in trading some loss of accuracy in exchange for simulation speed, which leads to constructing simulation models that focus on some design aspects and provide abstraction of others. A simulation model can provide an abstraction of the simulated hardware in three directions:

- *Computation abstraction*. A hardware component computes a high level function by carrying out a series of small steps executed by composing logical gates. In a virtual prototyping environment, it is often possible to compute the high level function directly by using the available computing resources on the simulation host machine, thus abstracting the hardware function.
- *Communication abstraction*. Hardware components communicate together using some wiring, and some protocol to transmit the data. Simulation of the communication and the particular protocol may be irrelevant for the purpose of virtual prototyping: communication can be abstracted into higher level data transmission functions.
- *Timing Abstraction*. In a cycle accurate simulator, there are multiple simulation tasks, and each task makes some progress on each clock cycle, but this is slowing down the simulation. In a virtual prototyping experiment, one may not need to so precise timing information: coarser time abstractions can be defined allowing for faster simulation.

The cornerstone of a virtual prototyping platform is the component that simulates the processor(s) of the platform, and its associated peripherals. Such simulation can be *static* or *dynamic*.

3.6. Research Objectives

The challenges addressed by team TEA support the claim that sound Cyber-Physical System design (including embedded, reactive, and concurrent systems altogether) should consider (logical, formal) time modelling as a central aspect.

In this aim, architectural specifications found in software engineering are a natural focal point to start from. Architecture descriptions organise a system model into manageable components, establish clear interfaces between them, and help correct integration of these components during system design.

The definition of a formal design methodology to support the heterogeneous modelling of time in architecture descriptions demands the elaboration of sound mathematical foundations and the development of formal calculi methods to instrument them that constitute the research program of team TEA.

3.6.1. Objective n. 1 – Semantics and specification of time in system design

Time systems. To mitigate and generalise algebraic representations of time, we propose to introduce the paradigm of "time system" (type systems to represent time). Just as a type system abstracts data carried along operations in a program, a time system abstracts the causal interaction of that program module or hardware element with its environment, its pre and post conditions, its assumptions and guarantees, either logical or numerical. Instances of the concept of time system we envision are the clock calculi found in data-flow synchronous languages like Signal, Lustre and its different incarnations. All are bound to a particular model of time.

To gain generality and compositionality, we wish to proceed from recent developments on hybrid types [0] (linked to interface and contract theories), refinement types [0], value-dependant type [0] theories, to formally define a time system.

[0] *Hybrid type checking*. K.W. Knowles and C. Flanagan. ACM Transactions on Programming languages and systems, 32(2). ACM, 2010

[0] *Abstract Refinement Types*. N. Vazou, P. Rondon, and R. Jhala. European Symposium on Programming. Springer, 2013.

[0] *Secure distributed programming with value-dependent types*. N. Swamy, et al. International Conference on Functional Programming. Springer, 2011.

The principle of these type systems is to allow data-types inferred in the program with properties, possibly temporal, pertaining, for instance, to the algebraic domain on their value, or any algebraic property related to its computation: effect, memory usage [0], pre-post condition, value-range, cost, speed, time.

In the quest of an appropriate algebra for time, we are studying both the CCSL and PSL standards and, more generally, Kleene algebras [0] which offer greater expressivity in the prospect of timed specification as well as refinement checking and verification [00].

Being grounded on type and domain theories, a time system can naturally be equipped with program analysis techniques based on type inference (for data-type inference) or abstract interpretation (for program properties inference) [0]. We intend to use and learn from existing open-source implementations in this field of research [0] in order to prototype our solution.

Relating time systems. Just as a time system formally represents the timed behaviour of a given component, timing relations (abstraction and refinement) represent interaction among components. Logically, their specification should be the role of a module system, and verifying their conformance that of a module checking algorithm.

Scalability and compositionality dictate the use of assume-guarantee reasoning, as found in interface automata and contract algebra, in order to facilitate composition by behavioural sub-typing, in the spirit of the (static) contract-based formalism proposed by Passerone et al. [00].

To further elaborate a formal verification approach, we will additionally consider notions of refinement calculi based on temporal logic [0], in order to possibly extend our interface and contract theories with liveness properties. The definition of a module/interface for timed architectures should hence proceed directly from the definition of its time system, using mostly existing theoretical results on the matter of module systems, interface and contract theories.

Conformance of time relations. Verification problems encompassing heterogeneously timed specifications are common and of great variety: checking correctness between abstract and concrete time models relates to desynchronisation (from synchrony to asynchrony) and scheduling analysis (from synchrony to hardware). More generally, they can be perceived from heterogeneous timing viewpoints (e.g. mapping a synchronous-time software on a real-time middleware or hardware).

This perspective demands capabilities not only to inject time models one into the other (by abstract interpretation, using refinement calculi), to compare time abstractions one another (using simulation, refinement, bisimulation, equivalence relations) but also to prove more specific properties (synchronisation, determinism, endochrony).

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[0] *Region-based memory management*. Tofte, M., Talpin, J.-P. Information and Computation, 132(2). Academic Press, 1997.

[0] *Automated reasoning in Kleene algebra*. P. Höfner and G. Struth. Conference on Automated Reasoning. Springer, 2007.

[0] *Algebraic Verification Method for SEREs Properties via Groebner Bases Approaches*. N. Zhou, J. Wu, X. Gao. Journal of Applied Mathematics. Hindawi, 2013

[0] *From monadic logic to PSL*. M. Y. Vardi. Pillars of Computer Science, 2008.

[0] *Timed polyhedra analysis for synchronous languages*. Besson, F., Jensen, T., Talpin, J.-P. Static Analysis Symposium. Springer, 1999.

[0] The Microsoft F* project, https://research.microsoft.com/en-us/projects/fstar.

[0] *A contract-based formalism for the specification of heterogeneous systems*. L. Benvenistu, A. Ferrari, L. Mangeruca, E. Mazzi, R. Passerone, C. Sofronis. Forum on design languages, 2008

[0] *Moving from Specifications to Contracts in Component-Based Design.* S. Bauer, A. David, R. Hennicker, K. Larsen, A. Legay, U. Nyman, A. Wasowski. Fundamental Aspects in Software Engineering. Springer, 2012

[0] *Refinement Calculus: A Systematic Introduction*. R.J. Back, J. von Wright. Springer, 1998.

In the spirit of our recent work developing an abstract scheduling theory, we want to develop a method of abstract interpretation [0] to reason about the abstraction and refinement of heterogeneous timed specifications in the aim of checking their conformance. A source of inspiration in that prospect is the notion of contract abstraction [0]. To this end, we plan to use SAT-SMT solving techniques to check conformance of abstracted time constraints, in a way which we previously experienced with the automated code generation validation of Polychrony [000].

To check conformance between heterogeneously timed specifications, we will consider variants of the abstract interpretation framework proposed by Bertrane et al. [0] to inject properties from one time domain into another, be it continuous [0] or discrete [0].

This will for instance enable the possibility of verifying cross-domain properties, e.g. cost v.s. power v.s. performance v.s. software mapping. This will allow to formalise intuitions such as that this typical inter-domain constraint: the cost of a system has an impact on the system's controlability; and allow to formally explain why: lower cost means hardware with lower performances, which means longer WCRTs, which means longer end-to-end latency, which may result in a response-time longer than controllability limits. This particular topic (which we could call cross-domain conformance checking) has not been studied in the related literature (on contract-based design, for instance), and could be based on both abstraction techniques, e.g. linear abstractions, or morphisms between domains or even discrete relations, e.g. a simple catalog or "price list" relating price and performance for a data-base of hardware components.

3.6.2. Objective n. 2 – A standard for modelling time in system design

A second objective, to be developed in parallel and synergy to objective n. 1, is the definition of an architecture-specific specification formalism, that would serve as semantic foundation, structure and repository for tooling a component-based design methodology with semantic analysis, to synthesise component interfaces, and formal methods, to verify specified requirements.

In project TEA, it will take form by the definition and tooling of a time annex for the AADL standard, based on the theory developed in objective n. 1. The aim of the AADL time annex is to formalise the logical and physical timing properties of architecture models and represent them as constraints expressed using regular grammars (like in PSL), or using the process calculus of CCSL.

This is an objective reminiscent and in direct application of the principle of time system (objective n.1). We not only want to model time in the heterogeneous logical and physical constituents in an AADL specification, but relate them, and verify the correctness of their composition.

Our aim is to start from the modelling standards AADL and CCSL to define a standard for time in system design. Our contribution will be formalised by a timing annex for the AADL and tools collaboratively developed to support its use. Our first milestone in this prospect is a report [0] of recommendations accepted by the AADL committee. Our next step, the submission of a time annex by team TEA at the SAE consortium, will

[0] *La vérification de programmes par interprétation abstraite*. P. Cousot. Séminaire au Collège de France, 2008.

[0] *Compositional contract abstraction for system design*. A. Benveniste, D. Nickovic, T. Henzinger.

[0] *Efficient deadlock detection for polychronous data-flow specifications*. C. Ngo, J.-P. Talpin, T. Gautier. Electronic System Level Synthesis Conference (ESLSYN'14). IEEE, 2014.

[0] *Formal verification of synchronous data-flow program transformations toward certified compilation*. V.-C. Ngo, J.-P. Talpin, Gautier, P. Le Guernic, L. Besnard. Frontiers of Computer Systems. Springer, 2013.

[0] *Enhancing the Compilation of Synchronous Dataflow Programs with a Combined Numerical-Boolean Abstraction*. P. Feautrier, A. Gamatié and L. Gonnord. Journal of Computing, 1(4). Computer Society of India, 2012.

[0] *Temporal Abstract Domains*. J. Bertrane. International Conference on Engineering of Complex Computer Systems. IEEE, 2011

[0] *Abstract Interpretation of the Physical Inputs of Embedded Programs*. O. Bouissou, M. Martel. Verification, Model Checking, and Abstract Interpretation. LNCS 4905, Springer, 2008

[0] *Proving the Properties of Communicating Imperfectly-Clocked Synchronous Systems*. J. Bertrane. Static Analysis Symposium. Springer, 2006

[0] *"Logically timed specifications in the AADL – Recommendations to the SAE committee on AADL*. L. Besnard, E. Borde, P. Dissaux, T. Gautier, P. Le Guernic, J.-P. Talpin, H. Yu. Inria Technical Report n.446, 2014.

employ the principles exposed in objective n.1 in order to formally define a modular and scalable specification formalism to specify heterogeneous timing constraints in the AADL.

Then, the specification of timing relations between AADL objects will be made explicit by contracts. Together with these contracts, we will then formally define abstraction and refinement relation in order to inject properties assumed by one component into the time model guaranteed by another, and vice versa. Lastly, conformance-checking abstracted contracts will be supported by state-of-the-art verification tools. This all will define a design methodology for time in the AADL, and our very last step will be to tool this methodology and provide a reference implementation.

3.6.3. Objective n. 3 – Applications to real-time scheduling

As a prime application of formal methods for interacting time models, scheduling thousands of program blocks or modules found on modern embedded architecture poses a challenging problem. It simply defies known bounds of complexity theory in the field. It is an issue that requires a particular address, because it would find direct industrial impact in present collaborative projects in which we are involved.

One recent milestone in the prospect of large-scale scheduling is the development of abstract affine scheduling [0]. It consists, first, of approximating threads communication patterns in Safety-Critical Java using cyclo-static data-flow graphs and affine functions. Then, it uses state of the art ILP techniques to find optimal schedules and concretise them as real-time schedules for Safety Critical Java programs [00]

To develop the underlying theory of this promising research topic, we first need to deepen the theoretical foundation to establish links between scheduling analysis and abstraction interpretation [0].

The theory of time system developed in objective n.1 offers the ideal framework to pursue this development. It amounts to representing scheduling constraints, inferred from programs, as types. It allows to formalise the target time model of the scheduler (the architecture, its middle-ware, its real-time system) and defines the basic concepts to verify assumptions made in one with promises offered by the other: contract verification or, in this case, synthesis. Objective n.3 is hence defined as a direct application of objective n.1.

3.6.4. Objective n. 4 – Applications to virtual prototyping

A solution usually adopted to handle time in virtual prototyping is to manage hierarchical time scales, use component abstractions where possible to gain performance, use refinement to gain accuracy where needed. Localised time abstraction may not only yield faster simulation, but facilitate also verification and synthesis (e.g. synchronous abstractions of physically distributed systems). Such an approach requires computations and communications to be harmoniously discretised and abstracted from originally heterogeneous viewpoints onto a structuring, articulating, pivot model, for concerted reasoning about time and scheduling of events in a way that ensures global system specification correctness.

Just as model checking usually employs goal-directed abstraction techniques, in order to approximate parts of the model that are not in the path of the property to check, we plan to equivalently define, possibly semi-automate, abstraction techniques to approximate the time model of system components that do not directly influence timing properties to evaluate.

In the short term these component models could be based on libraries of predefined models of different levels of abstractions. Such abstractions are common in large programming workbench for hardware modelling, such as SystemC, but less so, because of the engineering required, for virtual prototyping platforms. Additionally, the level of abstraction required to simulate components could simply (and best) be specified manually by annotating the architecture specification.

[0] *Buffer minimization in earliest-deadline first scheduling of dataflow graphs*. A. Bouakaz and J.-P. Talpin. Conference on Languages, Compilers and Tools for Embedded Systems. ACM, June 2013.

[0] *Affine data-flow graphs for the synthesis of hard real-time applications*. A. Bouakaz, J.-P. Talpin, and J. Vitek. Application of Concurrency to System Design. IEEE Press, June 2012.

[0] *Design of Safety-Critical Java Level 1 Applications Using Affine Abstract Clocks*. A. Bouakaz and J.-P. Talpin. International Workshop on Software and Compilers for Embedded Systems. ACM, June 2013.

[0] *Abstraction-Refinement for Priority-Driven Scheduling of Static Dataflow Graphs*. Submitted for publication, 2014.

The approach of team TEA provides an additional ingredient in the form of rich component interfaces. It therefore dictates to further investigate the combined use of conventional virtual prototyping libraries, defined as executable abstractions of real hardware, with executable component simulators synthesised from rich interface specifications (using, e.g., conventional compiling techniques used for synchronous programs).

Just as virtual integration consists of synthesising the verification model of an architecture specification, virtual prototyping can be seen as synthesising an executable simulator from a model in, e.g., the spirit of the A-350 DMS case study that was realised by team ESPRESSO in the frame of Artemisia project CESAR [0].

[0] *System-level co-simulation of integrated avionics using polychrony*. Yu, H., Ma, Y., Glouche, Y., Talpin, J.-P., Besnard, L., Gautier, T., Le Guernic, P., Toom, A., and Laurent, O. ACM Symposium on Applied Computing. ACM, 2011.

ASPI Project-Team

3. Research Program

3.1. Interacting Monte Carlo methods and particle approximation of Feynman–Kac distributions

Monte Carlo methods are numerical methods that are widely used in situations where (i) a stochastic (usually Markovian) model is given for some underlying process, and (ii) some quantity of interest should be evaluated, that can be expressed in terms of the expected value of a functional of the process trajectory, which includes as an important special case the probability that a given event has occurred. Numerous examples can be found, e.g. in financial engineering (pricing of options and derivative securities) [36], in performance evaluation of communication networks (probability of buffer overflow), in statistics of hidden Markov models (state estimation, evaluation of contrast and score functions), etc. Very often in practice, no analytical expression is available for the quantity of interest, but it is possible to simulate trajectories of the underlying process. The idea behind Monte Carlo methods is to generate independent trajectories of this process or of an alternate instrumental process, and to build an approximation (estimator) of the quantity of interest in terms of the weighted empirical probability distribution associated with the resulting independent sample. By the law of large numbers, the above estimator converges as the size N of the sample goes to infinity, with rate $1/\sqrt{N}$ and the asymptotic variance can be estimated using an appropriate central limit theorem. To reduce the variance of the estimator, many variance reduction techniques have been proposed. Still, running independent Monte Carlo simulations can lead to very poor results, because trajectories are generated *blindly*, and only afterwards are the corresponding weights evaluated. Some of the weights can happen to be negligible, in which case the corresponding trajectories are not going to contribute to the estimator, i.e. computing power has been wasted.

A recent and major breakthrough, has been the introduction of interacting Monte Carlo methods, also known as sequential Monte Carlo (SMC) methods, in which a whole (possibly weighted) sample, called *system of particles*, is propagated in time, where the particles

- *explore* the state space under the effect of a *mutation* mechanism which mimics the evolution of the underlying process,
- and are *replicated* or *terminated*, under the effect of a *selection* mechanism which automatically concentrates the particles, i.e. the available computing power, into regions of interest of the state space.

In full generality, the underlying process is a discrete–time Markov chain, whose state space can be

> finite, continuous, hybrid (continuous / discrete), graphical, constrained, time varying, pathwise, etc.,

the only condition being that it can easily be *simulated*.

In the special case of particle filtering, originally developed within the tracking community, the algorithms yield a numerical approximation of the optimal Bayesian filter, i.e. of the conditional probability distribution of the hidden state given the past observations, as a (possibly weighted) empirical probability distribution of the system of particles. In its simplest version, introduced in several different scientific communities under the name of *bootstrap filter* [38], *Monte Carlo filter* [43] or *condensation* (conditional density propagation) algorithm [40], and which historically has been the first algorithm to include a redistribution step, the selection mechanism is governed by the likelihood function: at each time step, a particle is more likely to survive and to replicate at the next generation if it is consistent with the current observation. The algorithms also provide as a by–product a numerical approximation of the likelihood function, and of many other contrast functions for parameter estimation in hidden Markov models, such as the prediction error or the conditional least–squares criterion.

Particle methods are currently being used in many scientific and engineering areas

> positioning, navigation, and tracking [39], [33], visual tracking [40], mobile robotics [34], [55], ubiquitous computing and ambient intelligence, sensor networks, risk evaluation and simulation of rare events [37], genetics, molecular simulation [35], etc.

Other examples of the many applications of particle filtering can be found in the contributed volume [22] and in the special issue of *IEEE Transactions on Signal Processing* devoted to *Monte Carlo Methods for Statistical Signal Processing* in February 2002, where the tutorial paper [23] can be found, and in the textbook [52] devoted to applications in target tracking. Applications of sequential Monte Carlo methods to other areas, beyond signal and image processing, e.g. to genetics, can be found in [51]. A recent overview can also be found in [25].

Particle methods are very easy to implement, since it is sufficient in principle to simulate independent trajectories of the underlying process. The whole problematic is multidisciplinary, not only because of the already mentioned diversity of the scientific and engineering areas in which particle methods are used, but also because of the diversity of the scientific communities which have contributed to establish the foundations of the field

> target tracking, interacting particle systems, empirical processes, genetic algorithms (GA), hidden Markov models and nonlinear filtering, Bayesian statistics, Markov chain Monte Carlo (MCMC) methods.

These algorithms can be interpreted as numerical approximation schemes for Feynman–Kac distributions, a pathwise generalization of Gibbs–Boltzmann distributions, in terms of the weighted empirical probability distribution associated with a system of particles. This abstract point of view [31], [29], has proved to be extremely fruitful in providing a very general framework to the design and analysis of numerical approximation schemes, based on systems of branching and / or interacting particles, for nonlinear dynamical systems with values in the space of probability distributions, associated with Feynman–Kac distributions. Many asymptotic results have been proved as the number N of particles (sample size) goes to infinity, using techniques coming from applied probability (interacting particle systems, empirical processes [56]), see e.g. the survey article [31] or the textbooks [29], [28], and references therein

> convergence in ^{p}, convergence as empirical processes indexed by classes of functions, uniform convergence in time, see also [48], [49], central limit theorem, see also [45], propagation of chaos, large deviations principle, etc.

The objective here is to systematically study the impact of the many algorithmic variants on the convergence results.

3.2. Statistics of HMM

Hidden Markov models (HMM) form a special case of partially observed stochastic dynamical systems, in which the state of a Markov process (in discrete or continuous time, with finite or continuous state space) should be estimated from noisy observations. The conditional probability distribution of the hidden state given past observations is a well–known example of a normalized (nonlinear) Feynman–Kac distribution, see 3.1 . These models are very flexible, because of the introduction of latent variables (non observed) which allows to model complex time dependent structures, to take constraints into account, etc. In addition, the underlying Markovian structure makes it possible to use numerical algorithms (particle filtering, Markov chain Monte Carlo methods (MCMC), etc.) which are computationally intensive but whose complexity is rather small. Hidden Markov models are widely used in various applied areas, such as speech recognition, alignment of biological sequences, tracking in complex environment, modeling and control of networks, digital communications, etc.

Beyond the recursive estimation of a hidden state from noisy observations, the problem arises of statistical inference of HMM with general state space [26], including estimation of model parameters, early monitoring and diagnosis of small changes in model parameters, etc.

Large time asymptotics A fruitful approach is the asymptotic study, when the observation time increases to infinity, of an extended Markov chain, whose state includes (i) the hidden state, (ii) the observation, (iii) the prediction filter (i.e. the conditional probability distribution of the hidden state given observations at all previous time instants), and possibly (iv) the derivative of the prediction filter with respect to the parameter. Indeed, it is easy to express the log–likelihood function, the conditional least–squares criterion, and many other clasical contrast processes, as well as their derivatives with respect to the parameter, as additive functionals of the extended Markov chain.

The following general approach has been proposed

- first, prove an exponential stability property (i.e. an exponential forgetting property of the initial condition) of the prediction filter and its derivative, for a misspecified model,
- from this, deduce a geometric ergodicity property and the existence of a unique invariant probability distribution for the extended Markov chain, hence a law of large numbers and a central limit theorem for a large class of contrast processes and their derivatives, and a local asymptotic normality property,
- finally, obtain the consistency (i.e. the convergence to the set of minima of the associated contrast function), and the asymptotic normality of a large class of minimum contrast estimators.

This programme has been completed in the case of a finite state space [7], and has been generalized [32] under an uniform minoration assumption for the Markov transition kernel, which typically does only hold when the state space is compact. Clearly, the whole approach relies on the existence of an exponential stability property of the prediction filter, and the main challenge currently is to get rid of this uniform minoration assumption for the Markov transition kernel [30], [49], so as to be able to consider more interesting situations, where the state space is noncompact.

Small noise asymptotics Another asymptotic approach can also be used, where it is rather easy to obtain interesting explicit results, in terms close to the language of nonlinear deterministic control theory [44]. Taking the simple example where the hidden state is the solution to an ordinary differential equation, or a nonlinear state model, and where the observations are subject to additive Gaussian white noise, this approach consists in assuming that covariances matrices of the state noise and of the observation noise go simultaneously to zero. If it is reasonable in many applications to consider that noise covariances are small, this asymptotic approach is less natural than the large time asymptotics, where it is enough (provided a suitable ergodicity assumption holds) to accumulate observations and to see the expected limit laws (law of large numbers, central limit theorem, etc.). In opposition, the expressions obtained in the limit (Kullback–Leibler divergence, Fisher information matrix, asymptotic covariance matrix, etc.) take here a much more explicit form than in the large time asymptotics.

The following results have been obtained using this approach

- the consistency of the maximum likelihood estimator (i.e. the convergence to the set M of global minima of the Kullback–Leibler divergence), has been obtained using large deviations techniques, with an analytical approach [41],
- if the abovementioned set M does not reduce to the true parameter value, i.e. if the model is not identifiable, it is still possible to describe precisely the asymptotic behavior of the estimators [42]: in the simple case where the state equation is a noise–free ordinary differential equation and using a Bayesian framework, it has been shown that (i) if the rank r of the Fisher information matrix I is constant in a neighborhood of the set M, then this set is a differentiable submanifold of codimension r, (ii) the posterior probability distribution of the parameter converges to a random probability distribution in the limit, supported by the manifold M, absolutely continuous w.r.t. the Lebesgue measure on M, with an explicit expression for the density, and (iii) the posterior probability distribution of the suitably normalized difference between the parameter and its projection on the manifold M, converges to a mixture of Gaussian probability distributions on the normal spaces to the manifold M, which generalized the usual asymptotic normality property,

- it has been shown [50] that (i) the parameter dependent probability distributions of the observations are locally asymptotically normal (LAN) [47], from which the asymptotic normality of the maximum likelihood estimator follows, with an explicit expression for the asymptotic covariance matrix, i.e. for the Fisher information matrix I, in terms of the Kalman filter associated with the linear tangent linear Gaussian model, and (ii) the score function (i.e. the derivative of the log–likelihood function w.r.t. the parameter), evaluated at the true value of the parameter and suitably normalized, converges to a Gaussian r.v. with zero mean and covariance matrix I.

3.3. Multilevel splitting for rare event simulation

See 4.2 , and 5.1 , 5.2 , and 5.3 .

The estimation of the small probability of a rare but critical event, is a crucial issue in industrial areas such as

> nuclear power plants, food industry, telecommunication networks, finance and insurance industry, air traffic management, etc.

In such complex systems, analytical methods cannot be used, and naive Monte Carlo methods are clearly unefficient to estimate accurately very small probabilities. Besides importance sampling, an alternate widespread technique consists in multilevel splitting [46], where trajectories going towards the critical set are given offsprings, thus increasing the number of trajectories that eventually reach the critical set. As shown in [5], the Feynman–Kac formalism of 3.1 is well suited for the design and analysis of splitting algorithms for rare event simulation.

Propagation of uncertainty Multilevel splitting can be used in static situations. Here, the objective is to learn the probability distribution of an output random variable $Y = F(X)$, where the function F is only defined pointwise for instance by a computer programme, and where the probability distribution of the input random variable X is known and easy to simulate from. More specifically, the objective could be to compute the probability of the output random variable exceeding a threshold, or more generally to evaluate the cumulative distribution function of the output random variable for different output values. This problem is characterized by the lack of an analytical expression for the function, the computational cost of a single pointwise evaluation of the function, which means that the number of calls to the function should be limited as much as possible, and finally the complexity and / or unavailability of the source code of the computer programme, which makes any modification very difficult or even impossible, for instance to change the model as in importance sampling methods.

The key issue is to learn as fast as possible regions of the input space which contribute most to the computation of the target quantity. The proposed splitting methods consists in (i) introducing a sequence of intermediate regions in the input space, implicitly defined by exceeding an increasing sequence of thresholds or levels, (ii) counting the fraction of samples that reach a level given that the previous level has been reached already, and (iii) improving the diversity of the selected samples, usually using an artificial Markovian dynamics. In this way, the algorithm learns

- the transition probability between successive levels, hence the probability of reaching each intermediate level,
- and the probability distribution of the input random variable, conditionned on the output variable reaching each intermediate level.

A further remark, is that this conditional probability distribution is precisely the optimal (zero variance) importance distribution needed to compute the probability of reaching the considered intermediate level.

Rare event simulation To be specific, consider a complex dynamical system modelled as a Markov process, whose state can possibly contain continuous components and finite components (mode, regime, etc.), and the objective is to compute the probability, hopefully very small, that a critical region of the state space is reached by the Markov process before a final time T, which can be deterministic and fixed, or random (for instance the time of return to a recurrent set, corresponding to a nominal behaviour).

The proposed splitting method consists in (i) introducing a decreasing sequence of intermediate, more and more critical, regions in the state space, (ii) counting the fraction of trajectories that reach an intermediate region before time T, given that the previous intermediate region has been reached before time T, and (iii) regenerating the population at each stage, through redistribution. In addition to the non–intrusive behaviour of the method, the splitting methods make it possible to learn the probability distribution of typical critical trajectories, which reach the critical region before final time T, an important feature that methods based on importance sampling usually miss. Many variants have been proposed, whether

- the branching rate (number of offsprings allocated to a successful trajectory) is fixed, which allows for depth–first exploration of the branching tree, but raises the issue of controlling the population size,
- the population size is fixed, which requires a breadth–first exploration of the branching tree, with random (multinomial) or deterministic allocation of offsprings, etc.

Just as in the static case, the algorithm learns

- the transition probability between successive levels, hence the probability of reaching each intermediate level,
- and the entrance probability distribution of the Markov process in each intermediate region.

Contributions have been given to

- minimizing the asymptotic variance, obtained through a central limit theorem, with respect to the shape of the intermediate regions (selection of the importance function), to the thresholds (levels), to the population size, etc.
- controlling the probability of extinction (when not even one trajectory reaches the next intermediate level),
- designing and studying variants suited for hybrid state space (resampling per mode, marginalization, mode aggregation),

and in the static case, to

- minimizing the asymptotic variance, obtained through a central limit theorem, with respect to intermediate levels, to the Metropolis kernel introduced in the mutation step, etc.

A related issue is global optimization. Indeed, the difficult problem of finding the set M of global minima of a real–valued function V can be replaced by the apparently simpler problem of sampling a population from a probability distribution depending on a small parameter, and asymptotically supported by the set M as the small parameter goes to zero. The usual approach here is to use the cross–entropy method [53], [27], which relies on learning the optimal importance distribution within a prescribed parametric family. On the other hand, multilevel splitting methods could provide an alternate nonparametric approach to this problem.

3.4. Nearest neighbor estimates

This additional topic was not present in the initial list of objectives, and has emerged only recently.

In pattern recognition and statistical learning, also known as machine learning, nearest neighbor (NN) algorithms are amongst the simplest but also very powerful algorithms available. Basically, given a training set of data, i.e. an N–sample of i.i.d. object–feature pairs, with real–valued features, the question is how to generalize, that is how to guess the feature associated with any new object. To achieve this, one chooses some integer k smaller than N, and takes the mean–value of the k features associated with the k objects that are nearest to the new object, for some given metric.

In general, there is no way to guess exactly the value of the feature associated with the new object, and the minimal error that can be done is that of the Bayes estimator, which cannot be computed by lack of knowledge of the distribution of the object–feature pair, but the Bayes estimator can be useful to characterize the strength of the method. So the best that can be expected is that the NN estimator converges, say when the sample size N grows, to the Bayes estimator. This is what has been proved in great generality by Stone [54] for the mean square convergence, provided that the object is a finite–dimensional random variable, the feature is a square–integrable random variable, and the ratio k/N goes to 0. Nearest neighbor estimator is not the only local averaging estimator with this property, but it is arguably the simplest.

The asymptotic behavior when the sample size grows is well understood in finite dimension, but the situation is radically different in general infinite dimensional spaces, when the objects to be classified are functions, images, etc.

Nearest neighbor classification in infinite dimension In finite dimension, the k–nearest neighbor classifier is universally consistent, i.e. its probability of error converges to the Bayes risk as N goes to infinity, whatever the joint probability distribution of the pair, provided that the ratio k/N goes to zero. Unfortunately, this result is no longer valid in general metric spaces, and the objective is to find out reasonable sufficient conditions for the weak consistency to hold. Even in finite dimension, there are exotic distances such that the nearest neighbor does not even get closer (in the sense of the distance) to the point of interest, and the state space needs to be complete for the metric, which is the first condition. Some regularity on the regression function is required next. Clearly, continuity is too strong because it is not required in finite dimension, and a weaker form of regularity is assumed. The following consistency result has been obtained: if the metric space is separable and if some Besicovich condition holds, then the nearest neighbor classifier is weakly consistent. Note that the Besicovich condition is always fulfilled in finite dimensional vector spaces (this result is called the Besicovich theorem), and that a counterexample [3] can be given in an infinite dimensional space with a Gaussian measure (in this case, the nearest neighbor classifier is clearly nonconsistent). Finally, a simple example has been found which verifies the Besicovich condition with a noncontinuous regression function.

Rates of convergence of the functional k–nearest neighbor estimator Motivated by a broad range of potential applications, such as regression on curves, rates of convergence of the k–nearest neighbor estimator of the regression function, based on N independent copies of the object–feature pair, have been investigated when the object is in a suitable ball in some functional space. Using compact embedding theory, explicit and general finite sample bounds can be obtained for the expected squared difference between the k–nearest neighbor estimator and the Bayes regression function, in a very general setting. The results have also been particularized to classical function spaces such as Sobolev spaces, Besov spaces and reproducing kernel Hilbert spaces. The rates obtained are genuine nonparametric convergence rates, and up to our knowledge the first of their kind for k–nearest neighbor regression.

This emerging topic has produced several theoretical advances [1], [2] in collaboration with Gérard Biau (université Pierre et Marie Curie, ENS Paris and EPI CLASSIC, Inria Paris—Rocquencourt), and a possible target application domain has been identified in the statistical analysis of recommendation systems, that would be a source of interesting problems.

I4S Project-Team

3. Research Program

3.1. Introduction

In this section, the main features for the key monitoring issues, namely identification, detection, and diagnostics, are provided, and a particular instantiation relevant for vibration monitoring is described.

It should be stressed that the foundations for identification, detection, and diagnostics, are fairly general, if not generic. Handling high order linear dynamical systems, in connection with finite elements models, which call for using subspace-based methods, is specific to vibration-based SHM. Actually, one particular feature of model-based sensor information data processing as exercised in I4S, is the combined use of black-box or semi-physical models together with physical ones. Black-box and semi-physical models are, for example, eigenstructure parameterizations of linear MIMO systems, of interest for modal analysis and vibration-based SHM. Such models are intended to be identifiable. However, due to the large model orders that need to be considered, the issue of model order selection is really a challenge. Traditional advanced techniques from statistics such as the various forms of Akaike criteria (AIC, BIC, MDL, ...) do not work at all. This gives rise to new research activities specific to handling high order models.

Our approach to monitoring assumes that a model of the monitored system is available. This is a reasonable assumption, especially within the SHM areas. The main feature of our monitoring method is its intrinsic ability to the early warning of small deviations of a system with respect to a reference (safe) behavior under usual operating conditions, namely without any artificial excitation or other external action. Such a normal behavior is summarized in a reference parameter vector θ_0, for example a collection of modes and mode-shapes.

3.2. Identification

The behavior of the monitored continuous system is assumed to be described by a parametric model $\{\mathbf{P}_\theta\,,\,\theta\in\Theta\}$, where the distribution of the observations $(Z_0,...,Z_N)$ is characterized by the parameter vector $\theta\in\Theta$. An *estimating function*, for example of the form :

$$\mathcal{K}_N(\theta)=1/N\sum_{k=0}^{N}K(\theta,Z_k)$$

is such that $\mathbf{E}_\theta[\mathcal{K}_N(\theta)]=0$ for all $\theta\in\Theta$. In many situations, $\mathcal{K}$ is the gradient of a function to be minimized : squared prediction error, log-likelihood (up to a sign), ... For performing model identification on the basis of observations $(Z_0,...,Z_N)$, an estimate of the unknown parameter is then [61] :

$$\widehat{\theta}_N=\arg\{\theta\in\Theta\,:\,\mathcal{K}_N(\theta)=0\}$$

In many applications, such an approach must be improved in the following directions :

- *Recursive estimation:* the ability to compute $\widehat{\theta}_{N+1}$ simply from $\widehat{\theta}_N$;
- *Adaptive estimation:* the ability to *track* the true parameter θ^* when it is time-varying.

3.3. Detection

Our approach to on-board detection is based on the so-called asymptotic statistical local approach, which we have extended and adapted [5], [4], [2]. It is worth noticing that these investigations of ours have been initially motivated by a vibration monitoring application example. It should also be stressed that, as opposite to many monitoring approaches, our method does not require repeated identification for each newly collected data sample.

For achieving the early detection of small deviations with respect to the normal behavior, our approach generates, on the basis of the reference parameter vector θ_0 and a new data record, indicators which automatically perform :

- The early detection of a slight mismatch between the model and the data;
- A preliminary diagnostics and localization of the deviation(s);
- The tradeoff between the magnitude of the detected changes and the uncertainty resulting from the estimation error in the reference model and the measurement noise level.

These indicators are computationally cheap, and thus can be embedded. This is of particular interest in some applications, such as flutter monitoring.

As in most fault detection approaches, the key issue is to design a *residual*, which is ideally close to zero under normal operation, and has low sensitivity to noises and other nuisance perturbations, but high sensitivity to small deviations, before they develop into events to be avoided (damages, faults, ...). The originality of our approach is to :

- *Design* the residual basically as a *parameter estimating function*,
- *Evaluate* the residual thanks to a kind of central limit theorem, stating that the residual is asymptotically Gaussian and reflects the presence of a deviation in the parameter vector through a change in its own mean vector, which switches from zero in the reference situation to a non-zero value.

This is actually a strong result, which transforms any detection problem concerning a parameterized stochastic *process* into the problem of monitoring the mean of a Gaussian *vector*.

The behavior of the monitored system is again assumed to be described by a parametric model $\{\mathbf{P}_\theta\ ,\ \theta \in \Theta\}$, and the safe behavior of the process is assumed to correspond to the parameter value θ_0. This parameter often results from a preliminary identification based on reference data, as in module 3.2 .

Given a new N-size sample of sensors data, the following question is addressed : *Does the new sample still correspond to the nominal model* $\mathbf{P}_{\theta_0}$ *?* One manner to address this generally difficult question is the following. The asymptotic local approach consists in deciding between the nominal hypothesis and a *close* alternative hypothesis, namely :

$$\text{(Safe) } \mathbf{H}_0 :\ \theta = \theta_0 \quad \text{ and } \quad \text{(Damaged) } \mathbf{H}_1 :\ \theta = \theta_0 + \eta/\sqrt{N} \tag{3}$$

where η is an unknown but fixed change vector. A residual is generated under the form :

$$\zeta_N = 1/\sqrt{N}\ \sum_{k=0}^{N} K(\theta_0, Z_k) = \sqrt{N}\ \mathcal{K}_N(\theta_0)\ . \tag{4}$$

If the matrix $\mathcal{J}_N = -\,\mathbf{E}_{\theta_0}[\partial \mathcal{K}_N(\theta_0)]$ converges towards a limit $\mathcal{J}$, then, under mild mixing and stationarity assumptions, the central limit theorem shows [60] that the residual is asymptotically Gaussian :

$$\zeta_N \xrightarrow[N\,\to\,\infty]{} \begin{cases} \mathcal{N}(0,\Sigma) & \text{under } \mathbf{P}_{\theta_0}\ , \\ \\ \mathcal{N}(\mathcal{J}\,\eta,\Sigma) & \text{under } \mathbf{P}_{\theta_0+\eta/\sqrt{N}}\ , \end{cases} \tag{5}$$

where the asymptotic covariance matrix Σ can be estimated, and manifests the deviation in the parameter vector by a change in its own mean value. Then, deciding between $\eta = 0$ and $\eta \neq 0$ amounts to compute the following χ^2-test, provided that $\mathcal{J}$ is full rank and Σ is invertible :

$$\chi^2 = \overline{\zeta}^{\,T}\,\mathbf{F}^{-1}\,\overline{\zeta} \gtrless \lambda\ . \tag{6}$$

where

$$\overline{\zeta} \triangleq \mathcal{J}^T \Sigma^{-1} \zeta_N \quad \text{and} \quad \mathbf{F} \triangleq \mathcal{J}^T \Sigma^{-1} \mathcal{J} \tag{7}$$

With this approach, it is possible to decide, with a quantifiable error level, if a residual value is significantly different from zero, for assessing whether a fault/damage has occurred. It should be stressed that the residual and the sensitivity and covariance matrices $\mathcal{J}$ and Σ can be evaluated (or estimated) for the nominal model. In particular, it is *not* necessary to re-identify the model, and the sensitivity and covariance matrices can be pre-computed off-line.

3.4. Diagnostics

A further monitoring step, often called *fault isolation*, consists in determining which (subsets of) components of the parameter vector θ have been affected by the change. Solutions for that are now described. How this relates to diagnostics is addressed afterwards.

The question: *which (subsets of) components of θ have changed ?*, can be addressed using either nuisance parameters elimination methods or a multiple hypotheses testing approach [59].

In most SHM applications, a complex physical system, characterized by a generally non identifiable parameter vector Φ has to be monitored using a simple (black-box) model characterized by an identifiable parameter vector θ. A typical example is the vibration monitoring problem for which complex finite elements models are often available but not identifiable, whereas the small number of existing sensors calls for identifying only simplified input-output (black-box) representations. In such a situation, two different diagnosis problems may arise, namely diagnosis in terms of the black-box parameter θ and diagnosis in terms of the parameter vector Φ of the underlying physical model.

The isolation methods sketched above are possible solutions to the former. Our approach to the latter diagnosis problem is basically a detection approach again, and not a (generally ill-posed) inverse problem estimation approach [3]. The basic idea is to note that the physical sensitivity matrix writes $\mathcal{J}\mathcal{J}_{\Phi\theta}$, where $\mathcal{J}_{\Phi\theta}$ is the Jacobian matrix at Φ_0 of the application $\Phi \mapsto \theta(\Phi)$, and to use the sensitivity test for the components of the parameter vector Φ. Typically this results in the following type of directional test :

$$\chi^2_\Phi = \zeta^T \Sigma^{-1} \mathcal{J}\mathcal{J}_{\Phi\theta} \left(\mathcal{J}^T_{\Phi\theta} \mathcal{J}^T \Sigma^{-1} \mathcal{J}\mathcal{J}_{\Phi\theta}\right)^{-1} \mathcal{J}^T_{\Phi\theta} \mathcal{J}^T \Sigma^{-1} \zeta \gtrless \lambda \ . \tag{8}$$

It should be clear that the selection of a particular parameterization Φ for the physical model may have a non negligible influence on such type of tests, according to the numerical conditioning of the Jacobian matrices $\mathcal{J}_{\Phi\theta}$.

As a summary, the machinery in modules 3.2 , 3.3 and 3.4 provides us with a generic framework for designing monitoring algorithms for continuous structures, machines and processes. This approach assumes that a model of the monitored system is available. This is a reasonable assumption within the field of applications since most mechanical processes rely on physical principles which write in terms of equations, providing us with models. These important *modeling* and *parameterization* issues are among the questions we intend to investigate within our research program.

The key issue to be addressed within each parametric model class is the residual generation, or equivalently the choice of the *parameter estimating function*.

3.5. Subspace-based identification and detection

For reasons closely related to the vibrations monitoring applications, we have been investigating subspace-based methods, for both the identification and the monitoring of the eigenstructure (λ, ϕ_λ) of the state transition matrix F of a linear dynamical state-space system :

$$\left\{ \begin{array}{rcl} X_{k+1} & = & F\ X_k + V_{k+1} \\ Y_k & = & H\ X_k \end{array} \right. , \tag{9}$$

namely the $(\lambda, \varphi_\lambda)$ defined by :

$$\det\ (F - \lambda\ I) = 0, \quad (F - \lambda\ I)\ \phi_\lambda = 0, \quad \varphi_\lambda \triangleq H\ \phi_\lambda \tag{10}$$

The (canonical) parameter vector in that case is :

$$\theta \triangleq \left(\begin{array}{c} \Lambda \\ \mathrm{vec}\Phi \end{array} \right) \tag{11}$$

where Λ is the vector whose elements are the eigenvalues λ, Φ is the matrix whose columns are the φ_λ's, and vec is the column stacking operator.

Subspace-based methods is the generic name for linear systems identification algorithms based on either time domain measurements or output covariance matrices, in which different subspaces of Gaussian random vectors play a key role [62]. A contribution of ours, minor but extremely fruitful, has been to write the output-only covariance-driven subspace identification method under a form that involves a parameter estimating function, from which we define a *residual adapted to vibration monitoring* [1]. This is explained next.

3.5.1. Covariance-driven subspace identification.

Let $R_i \triangleq \mathbf{E}\left(Y_k\ Y_{k-i}^T\right)$ and:

$$\mathcal{H}_{p+1,q} \triangleq \left(\begin{array}{cccc} R_0 & R_1 & \vdots & R_{q-1} \\ R_1 & R_2 & \vdots & R_q \\ \vdots & \vdots & \vdots & \vdots \\ R_p & R_{p+1} & \vdots & R_{p+q-1} \end{array} \right) \triangleq \mathrm{Hank}\left(R_i\right) \tag{12}$$

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_k^T\right)$. Direct computations of the R_i's from the equations (10) lead to the well known key factorizations :

$$\begin{array}{rcl} R_i & = & HF^iG \\ \mathcal{H}_{p+1,q} & = & \mathcal{O}_{p+1}(H,F)\ \mathcal{C}_q(F,G) \end{array} \tag{13}$$

where:

$$\mathcal{O}_{p+1}(H,F) \triangleq \left(\begin{array}{c} H \\ HF \\ \vdots \\ HF^p \end{array} \right) \quad \text{and} \quad \mathcal{C}_q(F,G) \triangleq (G\ FG\ \cdots\ F^{q-1}G) \tag{14}$$

are the observability and controllability matrices, respectively. The observation matrix H is then found in the first block-row of the observability matrix $\mathcal{O}$. The state-transition matrix F is obtained from the shift invariance property of $\mathcal{O}$. The eigenstructure (λ, ϕ_λ) then results from (11).

Since the actual model order is generally not known, this procedure is run with increasing model orders.

3.5.2. Model parameter characterization.

Choosing the eigenvectors of matrix F as a basis for the state space of model (10) yields the following representation of the observability matrix:

$$\mathcal{O}_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi\Delta^p \end{pmatrix} \tag{15}$$

where $\Delta \triangleq \text{diag}(\Lambda)$, and Λ and Φ are as in (12). Whether a nominal parameter θ_0 fits a given output covariance sequence $(R_j)_j$ is characterized by [1]:

$$\mathcal{O}_{p+1}(\theta_0) \text{ and } \mathcal{H}_{p+1,q} \text{ have the same left kernel space.} \tag{16}$$

This property can be checked as follows. From the nominal θ_0, compute $\mathcal{O}_{p+1}(\theta_0)$ using (16), and perform e.g. a singular value decomposition (SVD) of $\mathcal{O}_{p+1}(\theta_0)$ for extracting a matrix U such that:

$$U^T\, U = I_s \text{ and } U^T\, \mathcal{O}_{p+1}(\theta_0) = 0 \tag{17}$$

Matrix U is not unique (two such matrices relate through a post-multiplication with an orthonormal matrix), but can be regarded as a function of θ_0. Then the characterization writes:

$$U(\theta_0)^T\, \mathcal{H}_{p+1,q} = 0 \tag{18}$$

3.5.3. Residual associated with subspace identification.

Assume now that *a reference θ_0 and a new sample $Y_1, \cdots, Y_N$ are available.* For checking whether the data agree with θ_0, the idea is to compute the empirical Hankel matrix $\widehat{\mathcal{H}}_{p+1,q}$:

$$\widehat{\mathcal{H}}_{p+1,q} \triangleq \text{Hank}\left(\widehat{R}_i\right), \quad \widehat{R}_i \triangleq 1/(N-i) \sum_{k=i+1}^{N} Y_k\, Y_{k-i}^T \tag{19}$$

and to define the residual vector:

$$\zeta_N(\theta_0) \triangleq \sqrt{N}\ \text{vec}\left(U(\theta_0)^T\, \widehat{\mathcal{H}}_{p+1,q}\right) \tag{20}$$

Let θ be the actual parameter value for the system which generated the new data sample, and $\mathbf{E}_\theta$ be the expectation when the actual system parameter is θ. From (19), we know that $\zeta_N(\theta_0)$ has zero mean when no change occurs in θ, and nonzero mean if a change occurs. Thus $\zeta_N(\theta_0)$ plays the role of a residual.

It is our experience that this residual has highly interesting properties, both for damage detection [1] and localization [3], and for flutter monitoring [8].

3.5.4. Other uses of the key factorizations.

Factorization (3.5.1) is the key for a characterization of the canonical parameter vector θ in (12), and for deriving the residual. Factorization (14) is also the key for :

- Proving consistency and robustness results [6];
- Designing an extension of covariance-driven subspace identification algorithm adapted to the presence and fusion of non-simultaneously recorded multiple sensors setups [7];
- Proving the consistency and robustness of this extension [9];
- Designing various forms of *input-output* covariance-driven subspace identification algorithms adapted to the presence of both known inputs and unknown excitations [10].

3.5.5. Research program

The research will first focus on the extension and implementation of current techniques as developed in I4S and IFSTTAR. Before doing any temperature rejection on large scale structures as planned, we need to develop good and accurate models of thermal fields. We also need to develop robust and efficient versions of our algorithms, mainly the subspace algorithms before envisioning linking them with physical models. Briefly, we need to mature our statistical toolset as well as our physical modeling before mixing them together later on.

3.5.5.1. Direct vibration modeling under temperature changes

This task builds upon what has been achieved in the CONSTRUCTIF project, where a simple formulation of the temperature effect has been exhibited, based on relatively simple assumptions. The next step is to generalize this modeling to a realistic large structure under complex thermal changes. Practically, temperature and resulting structural prestress and pre strains of thermal origin are not uniform and civil structures are complex. This leads to a fully 3D temperature field, not just a single value. Inertia effects also forbid a trivial prediction of the temperature based on current sensor outputs while ignoring past data. On the other side, the temperature is seen as a nuisance. That implies that any damage detection procedure has first to correct the temperature effect prior to any detection.

Modeling vibrations of structures under thermal prestress does and will play an important role in the static correction of kinematic measurements, in health monitoring methods based on vibration analysis as well as in durability and in the active or semi-active control of civil structures that by nature are operated under changing environmental conditions. As a matter of fact, using temperature and dynamic models the project aims at correcting the current vibration state from induced temperature effects, such that damage detection algorithms rely on a comparison of this thermally corrected current vibration state with a reference state computed or measured at a reference temperature. This approach is expected to cure damage detection algorithms from the environmental variations.

I4S will explore various ways of implementing this concept, notably within the FUI SIPRIS project.

3.5.5.2. Damage localization algorithms (in the case of localized damages such as cracks)

During the CONSTRUCTIF project, both feasibility and efficiency of some damage detection and localization algorithms were proved. Those methods are based on the tight coupling of statistical algorithms with finite element models. It has been shown that effective localization of some damaged elements was possible, and this was validated on a numerical simulated bridge deck model. Still, this approach has to be validated on real structures.

On the other side, new localization algorithms are currently investigated such as the one developed conjointly with University of Boston and tested within the framework of FP7 ISMS project. These algorithms will be implemented and tested on the PEGASE platform as well as all our toolset.

When possible, link with temperature rejection will be done along the lines of what has been achieved in the CONSTRUCTIF project.

3.5.5.3. Uncertainty quantification for system identification algorithms

Some emphasis will be put on expressing confidence intervals for system identification. It is a primary goal to take into account the uncertainty within the identification procedure, using either identification algorithms derivations or damage detection principles. Such algorithms are critical for both civil and aeronautical structures monitoring. It has been shown that confidence intervals for estimation parameters can theoretically be related to the damage detection techniques and should be computed as a function of the Fisher information matrix associated to the damage detection test. Based on those assumptions, it should be possible to obtain confidence intervals for a large class of estimates, from damping to finite elements models. Uncertainty considerations are also deeply investigated in collaboration with Dassault Aviation in Mellinger PhD thesis or with Northeastern University, Boston, within Gallegos PhD thesis.

3.5.5.4. Reflectometry-based methods for civil engineering structure health monitoring

For mechanical structures with a dominating geometrical axis so that they can be approximately considered one dimensional structures, some reflectometry-based methods initially developed for electrical cable monitoring have proved efficient for their health monitoring. Typical applications of such methods have been validated for the monitoring of external post-tensioned cables built with concrete bridges. Further studies are necessary to generalize this technology to other mechanical structures.

3.5.5.5. PEGASE platform

A new iteration called PEGASE 2 of our wireless platform has to be finalized (see Software section), in particular:

- Validation of PEGASE 2 mother board for its ability to recover energy from solar cells. Writing resulting abacus and user-guides...
- Discover and manage the DSP Library of PEGASE 2 (TI 5330 processor)
- Finalizing its main daughter boards:
  - 8 synchronous analog channel daughter board (finalized at 90
  - validation of the POE (Power Over Ethernet) daughter board
  - validation of the 3G daughter board (for GSM links)
  - Finalizing the supervisor (Matlab plugin...)

Figure 1. PEGASE board

IPSO Project-Team

3. Research Program

3.1. Structure-preserving numerical schemes for solving ordinary differential equations

Participants: François Castella, Philippe Chartier, Erwan Faou, Vilmart Gilles.

ordinary differential equation, numerical integrator, invariant, Hamiltonian system, reversible system, Lie-group system

In many physical situations, the time-evolution of certain quantities may be written as a Cauchy problem for a differential equation of the form

$$\begin{aligned} y'(t) &= f(y(t)), \\ y(0) &= y_0. \end{aligned} \tag{21}$$

For a given y_0, the solution $y(t)$ at time t is denoted $\varphi_t(y_0)$. For fixed t, φ_t becomes a function of y_0 called the *flow* of (1). From this point of view, a numerical scheme with step size h for solving (1) may be regarded as an approximation Φ_h of φ_h. One of the main questions of *geometric integration* is whether *intrinsic* properties of φ_t may be passed on to Φ_h.

This question can be more specifically addressed in the following situations:

3.1.1. Reversible ODEs

The system (1) is said to be ρ-reversible if there exists an involutive linear map ρ such that

$$\rho \circ \varphi_t = \varphi_t^{-1} \circ \rho = \varphi_{-t} \circ \rho. \tag{22}$$

It is then natural to require that Φ_h satisfies the same relation. If this is so, Φ_h is said to be *symmetric*. Symmetric methods for reversible systems of ODEs are just as much important as *symplectic* methods for Hamiltonian systems and offer an interesting alternative to symplectic methods.

3.1.2. ODEs with an invariant manifold

The system (1) is said to have an invariant manifold g whenever

$$\mathcal{M} = \{y \in \mathbb{R}^n; g(y) = 0\} \tag{23}$$

is kept *globally* invariant by φ_t. In terms of derivatives and for sufficiently differentiable functions f and g, this means that

$$\forall\, y \in \mathcal{M},\ g'(y)f(y) = 0.$$

As an example, we mention Lie-group equations, for which the manifold has an additional group structure. This could possibly be exploited for the space-discretisation. Numerical methods amenable to this sort of problems have been reviewed in a recent paper [60] and divided into two classes, according to whether they use g explicitly or through a projection step. In both cases, the numerical solution is forced to live on the manifold at the expense of some Newton's iterations.

3.1.3. Hamiltonian systems

Hamiltonian problems are ordinary differential equations of the form:

$$\begin{array}{rcccl} \dot{p}(t) & = & -\nabla_q H(p(t),q(t)) & \in & \mathbb{R}^d \\ \dot{q}(t) & = & \nabla_p H(p(t),q(t)) & \in & \mathbb{R}^d \end{array} \tag{24}$$

with some prescribed initial values $(p(0),q(0)) = (p_0,q_0)$ and for some scalar function H, called the Hamiltonian. In this situation, H is an invariant of the problem. The evolution equation (4) can thus be regarded as a differential equation on the manifold

$$\mathcal{M} = \{(p,q) \in \mathbb{R}^d \times \mathbb{R}^d; H(p,q) = H(p_0,q_0)\}.$$

Besides the Hamiltonian function, there might exist other invariants for such systems: when there exist d invariants in involution, the system (4) is said to be *integrable*. Consider now the parallelogram P originating from the point $(p,q) \in \mathbb{R}^{2d}$ and spanned by the two vectors $\xi \in \mathbb{R}^{2d}$ and $\eta \in \mathbb{R}^{2d}$, and let $\omega(\xi,\eta)$ be the sum of the *oriented* areas of the projections over the planes (p_i,q_i) of P,

$$\omega(\xi,\eta) = \xi^T J \eta,$$

where J is the *canonical symplectic* matrix

$$J = \begin{bmatrix} 0 & I_d \\ -I_d & 0 \end{bmatrix}.$$

A continuously differentiable map g from $\mathbb{R}^{2d}$ to itself is called symplectic if it preserves ω, i.e. if

$$\omega(g'(p,q)\xi, g'(p,q)\eta) = \omega(\xi,\eta).$$

A fundamental property of Hamiltonian systems is that their exact flow is symplectic. Integrable Hamiltonian systems behave in a very remarkable way: as a matter of fact, their invariants persist under small perturbations, as shown in the celebrated theory of Kolmogorov, Arnold and Moser. This behavior motivates the introduction of *symplectic* numerical flows that share most of the properties of the exact flow. For practical simulations of Hamiltonian systems, symplectic methods possess an important advantage: the error-growth as a function of time is indeed linear, whereas it would typically be quadratic for non-symplectic methods.

3.1.4. Differential-algebraic equations

Whenever the number of differential equations is insufficient to determine the solution of the system, it may become necessary to solve the differential part and the constraint part altogether. Systems of this sort are called differential-algebraic systems. They can be classified according to their index, yet for the purpose of this expository section, it is enough to present the so-called index-2 systems

$$\begin{array}{rcl} \dot{y}(t) & = & f(y(t),z(t)), \\ 0 & = & g(y(t)), \end{array} \tag{25}$$

where initial values $(y(0),z(0)) = (y_0,z_0)$ are given and assumed to be consistent with the constraint manifold. By constraint manifold, we imply the intersection of the manifold

$$\mathcal{M}_1 = \{y \in \mathbb{R}^n, g(y) = 0\}$$

and of the so-called hidden manifold

$$\mathcal{M}_2 = \{(y,z) \in \mathbb{R}^n \times \mathbb{R}^m, \frac{\partial g}{\partial y}(y) f(y,z) = 0\}.$$

This manifold $\mathcal{M} = \mathcal{M}_1 \bigcap \mathcal{M}_2$ is the manifold on which the exact solution $(y(t), z(t))$ of (5) lives.

There exists a whole set of schemes which provide a numerical approximation lying on $\mathcal{M}_1$. Furthermore, this solution can be projected on the manifold $\mathcal{M}$ by standard projection techniques. However, it it worth mentioning that a projection destroys the symmetry of the underlying scheme, so that the construction of a symmetric numerical scheme preserving $\mathcal{M}$ requires a more sophisticated approach.

3.2. Highly-oscillatory systems

Participants: François Castella, Philippe Chartier, Nicolas Crouseilles, Erwan Faou, Florian Méhats, Mohammed Lemou, Gilles Vilmart.

second-order ODEs, oscillatory solutions, Schrödinger and wave equations, step size restrictions.

In applications to molecular dynamics or quantum dynamics for instance, the right-hand side of (1) involves *fast* forces (short-range interactions) and *slow* forces (long-range interactions). Since *fast* forces are much cheaper to evaluate than *slow* forces, it seems highly desirable to design numerical methods for which the number of evaluations of slow forces is not (at least not too much) affected by the presence of fast forces.

A typical model of highly-oscillatory systems is the second-order differential equations

$$\ddot{q} \quad = \quad -\nabla V(q) \tag{26}$$

where the potential $V(q)$ is a sum of potentials $V = W + U$ acting on different time-scales, with $\nabla^2 W$ positive definite and $\|\nabla^2 W\| >> \|\nabla^2 U\|$. In order to get a bounded error propagation in the linearized equations for an explicit numerical method, the step size must be restricted according to

$$h\omega < C,$$

where C is a constant depending on the numerical method and where ω is the highest frequency of the problem, i.e. in this situation the square root of the largest eigenvalue of $\nabla^2 W$. In applications to molecular dynamics for instance, *fast* forces deriving from W (short-range interactions) are much cheaper to evaluate than *slow* forces deriving from U (long-range interactions). In this case, it thus seems highly desirable to design numerical methods for which the number of evaluations of slow forces is not (at least not too much) affected by the presence of fast forces.

Another prominent example of highly-oscillatory systems is encountered in quantum dynamics where the Schrödinger equation is the model to be used. Assuming that the Laplacian has been discretized in space, one indeed gets the *time*-dependent Schrödinger equation:

$$i\dot{\psi}(t) = \frac{1}{\varepsilon} H(t)\psi(t), \tag{27}$$

where $H(t)$ is finite-dimensional matrix and where ε typically is the square-root of a mass-ratio (say electron/ion for instance) and is small ($\varepsilon \approx 10^{-2}$ or smaller). Through the coupling with classical mechanics ($H(t)$ is obtained by solving some equations from classical mechanics), we are faced once again with two different time-scales, 1 and ε. In this situation also, it is thus desirable to devise a numerical method able to advance the solution by a time-step $h > \varepsilon$.

3.3. Geometric schemes for the Schrödinger equation

Participants: François Castella, Philippe Chartier, Erwan Faou, Florian Méhats, Gilles Vilmart.

Schrödinger equation, variational splitting, energy conservation.

Given the Hamiltonian structure of the Schrödinger equation, we are led to consider the question of energy preservation for time-discretization schemes.

At a higher level, the Schrödinger equation is a partial differential equation which may exhibit Hamiltonian structures. This is the case of the time-dependent Schrödinger equation, which we may write as

$$i\varepsilon\frac{\partial\psi}{\partial t} = H\psi, \tag{28}$$

where $\psi = \psi(x,t)$ is the wave function depending on the spatial variables $x = (x_1, \cdots, x_N)$ with $x_k \in \mathbb{R}^d$ (e.g., with $d = 1$ or 3 in the partition) and the time $t \in \mathbb{R}$. Here, ε is a (small) positive number representing the scaled Planck constant and i is the complex imaginary unit. The Hamiltonian operator H is written

$$H = T + V$$

with the kinetic and potential energy operators

$$T = -\sum_{k=1}^{N}\frac{\varepsilon^2}{2m_k}\Delta_{x_k} \quad \text{and} \quad V = V(x),$$

where $m_k > 0$ is a particle mass and Δ_{x_k} the Laplacian in the variable $x_k \in \mathbb{R}^d$, and where the real-valued potential V acts as a multiplication operator on ψ.

The multiplication by i in (8) plays the role of the multiplication by J in classical mechanics, and the energy $\langle\psi|H|\psi\rangle$ is conserved along the solution of (8), using the physicists' notations $\langle u|A|u\rangle = \langle u, Au\rangle$ where $\langle\ ,\ \rangle$ denotes the Hermitian L^2-product over the phase space. In quantum mechanics, the number N of particles is very large making the direct approximation of (8) very difficult.

The numerical approximation of (8) can be obtained using projections onto submanifolds of the phase space, leading to various PDEs or ODEs: see [64], [63] for reviews. However the long-time behavior of these approximated solutions is well understood only in this latter case, where the dynamics turns out to be finite dimensional. In the general case, it is very difficult to prove the preservation of qualitative properties of (8) such as energy conservation or growth in time of Sobolev norms. The reason for this is that backward error analysis is not directly applicable for PDEs. Overwhelming these difficulties is thus a very interesting challenge.

A particularly interesting case of study is given by symmetric splitting methods, such as the Strang splitting:

$$\psi_1 = \exp\left(-i(\delta t)V/2\right)\exp\left(i(\delta t)\Delta\right)\exp\left(-i(\delta t)V/2\right)\psi_0 \tag{29}$$

where δt is the time increment (we have set all the parameters to 1 in the equation). As the Laplace operator is unbounded, we cannot apply the standard methods used in ODEs to derive long-time properties of these schemes. However, its projection onto finite dimensional submanifolds (such as Gaussian wave packets space or FEM finite dimensional space of functions in x) may exhibit Hamiltonian or Poisson structure, whose long-time properties turn out to be more tractable.

3.4. High-frequency limit of the Helmholtz equation

Participant: François Castella.

waves, Helmholtz equation, high oscillations.

The Helmholtz equation models the propagation of waves in a medium with variable refraction index. It is a simplified version of the Maxwell system for electro-magnetic waves.

The high-frequency regime is characterized by the fact that the typical wavelength of the signals under consideration is much smaller than the typical distance of observation of those signals. Hence, in the high-frequency regime, the Helmholtz equation at once involves highly oscillatory phenomena that are to be described in some asymptotic way. Quantitatively, the Helmholtz equation reads

$$i\alpha_\varepsilon u_\varepsilon(x) + \varepsilon^2 \Delta_x u_\varepsilon + n^2(x) u_\varepsilon = f_\varepsilon(x). \tag{30}$$

Here, ε is the small adimensional parameter that measures the typical wavelength of the signal, $n(x)$ is the space-dependent refraction index, and $f_\varepsilon(x)$ is a given (possibly dependent on ε) source term. The unknown is $u_\varepsilon(x)$. One may think of an antenna emitting waves in the whole space (this is the $f_\varepsilon(x)$), thus creating at any point x the signal $u_\varepsilon(x)$ along the propagation. The small $\alpha_\varepsilon > 0$ term takes into account damping of the waves as they propagate.

One important scientific objective typically is to describe the high-frequency regime in terms of *rays* propagating in the medium, that are possibly refracted at interfaces, or bounce on boundaries, etc. Ultimately, one would like to replace the true numerical resolution of the Helmholtz equation by that of a simpler, asymptotic model, formulated in terms of rays.

In some sense, and in comparison with, say, the wave equation, the specificity of the Helmholtz equation is the following. While the wave equation typically describes the evolution of waves between some initial time and some given observation time, the Helmholtz equation takes into account at once the propagation of waves over *infinitely long* time intervals. Qualitatively, in order to have a good understanding of the signal observed in some bounded region of space, one readily needs to be able to describe the propagative phenomena in the whole space, up to infinity. In other words, the "rays" we refer to above need to be understood from the initial time up to infinity. This is a central difficulty in the analysis of the high-frequency behaviour of the Helmholtz equation.

3.5. From the Schrödinger equation to Boltzmann-like equations

Participant: François Castella.

Schrödinger equation, asymptotic model, Boltzmann equation.

The Schrödinger equation is the appropriate way to describe transport phenomena at the scale of electrons. However, for real devices, it is important to derive models valid at a larger scale.

In semi-conductors, the Schrödinger equation is the ultimate model that allows to obtain quantitative information about electronic transport in crystals. It reads, in convenient adimensional units,

$$i\partial_t \psi(t,x) = -\frac{1}{2}\Delta_x \psi + V(x)\psi, \tag{31}$$

where $V(x)$ is the potential and $\psi(t,x)$ is the time- and space-dependent wave function. However, the size of real devices makes it important to derive simplified models that are valid at a larger scale. Typically, one wishes to have kinetic transport equations. As is well-known, this requirement needs one to be able to describe "collisions" between electrons in these devices, a concept that makes sense at the macroscopic level, while it does not at the microscopic (electronic) level. Quantitatively, the question is the following: can one obtain the Boltzmann equation (an equation that describes collisional phenomena) as an asymptotic model for the Schrödinger equation, along the physically relevant micro-macro asymptotics? From the point of view of modelling, one wishes here to understand what are the "good objects", or, in more technical words, what are the relevant "cross-sections", that describe the elementary collisional phenomena. Quantitatively, the Boltzmann equation reads, in a simplified, linearized, form :

$$\partial_t f(t,x,v) = \int_{\mathbf{R}^3} \sigma(v,v') \, [f(t,x,v') - f(t,x,v)] dv'. \tag{32}$$

Here, the unknown is $f(x,v,t)$, the probability that a particle sits at position x, with a velocity v, at time t. Also, $\sigma(v,v')$ is called the cross-section, and it describes the probability that a particle "jumps" from velocity v to velocity v' (or the converse) after a collision process.

DYLISS Project-Team

3. Research Program

3.1. Knowledge representation with constraint programming

Biological networks are built with data-driven approaches aiming at translating genomic information into a functional map. Most methods are based on a probabilistic framework which defines a probability distribution over the set of models. The reconstructed network is then defined as the most likely model given the data. In the last few years, our team has investigated an alternative perspective where each observation induces a set of constraints - related to the steady state response of the system dynamics - on the set of possible values in a network of fixed topology. The methods that we have developed complete the network with product states at the level of nodes and influence types at the level of edges, able to globally explain experimental data. In other words, the selection of relevant information in the model is no more performed by selecting *the* network with the highest score, but rather by exploring the complete space of models satisfying constraints on the possible dynamics supported by prior knowledge and observations. In the (common) case when there is no model satisfying all the constraints, we need to relax the problem and to study the space of corrections to prior knowledge in order to fit reasonably with observation data. In this case, this issue is modeled as combinatorial (sub)-optimization issues. In both cases, common properties to all solutions are considered as a robust information about the system, as they are independent from the choice of a single solution to the satisfiability problem (in the case of existing solutions) or to the optimization problem (in the case of required corrections to the prior knowledge) [5].

Solving these computational issues requires addressing NP-hard qualitative (non-temporal) issues. We have developed a long-term collaboration with Potsdam University in order to use a logical paradigm named **Answer Set Programming** [45], [53] to solve these constraint satisfiability and combinatorial optimization issues. Applied on transcriptomic or cancer networks, our methods identified which regions of a large-scale network shall be corrected [46], and proposed robust corrections [4]. See Fig. 1 for details. The results obtained so far suggest that this approach is compatible with efficiency, scale and expressivity needed by biological systems. Our goal is now to provide **formal models of queries on biological networks** with the focus of integrating dynamical information as explicit logical constraints in the modeling process. This would definitely introduce such logical paradigms as a powerful approach to build and query reconstructed biological systems, in complement to discriminative approaches. Notice that our main issue is in the field of knowledge representation. More precisely, we do not wish to develop new solvers or grounders, a self-contained computational issue which is addressed by specialized teams such as our collaborator team in Potsdam. Our goal is rather to investigate whether progresses in the field of constraint logical programming, shown by the performance of ASP-solvers in several recent competitions, are now sufficient to address the complexity of constraint-satisfiability and combinatorial optimization issues explored in systems biology.

By exploring the complete space of models, our approach typically produces numerous candidate models compatible with the observations. We began investigating to what extent domain knowledge can further refine the analysis of the set of models by identifying classes of similar models, or by selecting the models that best fit biological knowledge. We anticipate that this will be particularly relevant when studying non-model species for which little is known but valuable information from other species can be transposed or adapted. These efforts consist in developing reasoning methods based on ontologies as formal representation of symbolic knowledge. We use Semantic Web tools such as SPARQL for querying and integrating large sources of external knowledge, and measures of semantic similarity and particularity for analyzing data.

Using these technologies requires to revisit and reformulate constraint-satisfiability problems at hand in order both to decrease the search space size in the grounding part of the process and to improve the exploration of this search space in the solving part of the process. Concretely, getting logical encoding for the optimization problems forces to clarify the roles and dependencies between parameters involved in the problem. This opens

the way to a refinement approach based on a fine investigation of the space of hypotheses in order to make it smaller and gain in the understanding of the system.

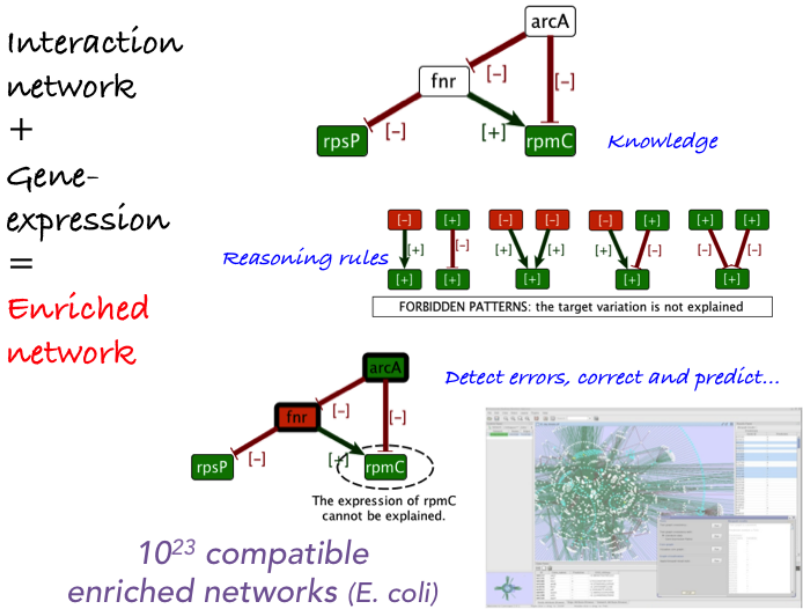


Figure 1.

An example of reasoning process in order to identify which expression of non-observed nodes (white nodes) are fixed by partial observations and rules derived from the system dynamics. The ASP-based logical approach is flexible enough to model in a single framework network characteristics (products, interactions, partial information on signs of regulations and observations) and static rules about the effects of the dynamics of the system. Extensions of this framework include the exhaustive search for system repair or more constrained dynamical rules. [5], [4] ***Step 1****. Regulation knowledge is represented as a signed oriented graph. Edge colors stand for regulatory effects (red/green→ inhibition or activation). Vertex colors stand for gene expression data (red/green→ under or over-expression).* ***Step 2****. Integrity constraints on the whole colored graph come from the necessity to find a consistent explanation of the link between regulation and expression.* ***Step 3****. The model allows both the prediction of values (e.g. for fnr in the figure) and the detection of contradictions (e.g. the expression level of rpmC is inconsistant with the regulation in the graph). .*

3.2. Probabilistic and symbolic dynamics

We work on new techniques to emphasize biological strategies that must occur to reproduce quantitative measurements in order to predict the quantitative response of a system at a larger-scale. Our framework mixes mechanistic and probabilistic modeling [1]. The system is modeled by an Event Transition Graph, that is, a **Markovian qualitative description of its dynamics** together with quantitative laws which describe the effect of the dynamic transitions over higher scale quantitative measurements. Then, a few time-series quantitative measurements are provided. Following an ergodic assumption and average case analysis properties, we know that a multiplicative accumulation law on a Markov chain asymptotically follows a log-normal law with explicit parameters [52]. This property can be derived into constraints to describe the set of admissible weighted Markov chains whose asymptotic behavior agrees with the quantitative measures at hand. A precise

study of this constrained space via local search optimization emphasizes the most important discrete events that must occur to reproduce the information at hand. These methods have been validated on the *E. coli* regulatory network benchmark. See Figure 2 for illustration. We now plan to apply these techniques to reduced networks representing the main pathways and actors automatically generated from the integrative methods developed in the former section. This requires to improve the range of dynamics that can be modeled by these techniques, as well as the efficiency and scalability of the local search algorithms.

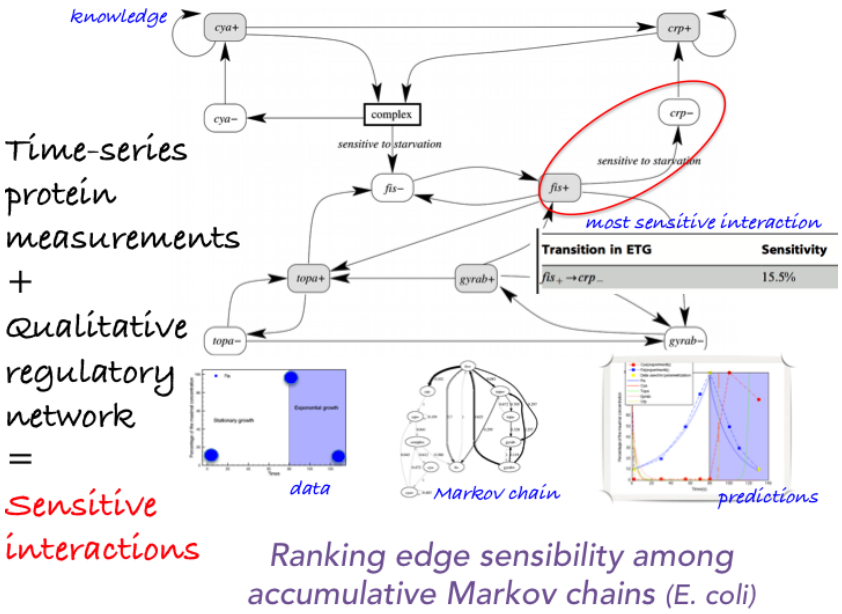


Figure 2.

Prediction of the quantitative behavior of a system using average-case analysis of dynamical systems and identification of key interactions [1].
Input data *are provided by a qualitative description of the system dynamics at the transcription level (interaction graph) and 3 concentration measurements of the* fis *protein (population scale). The method computes an* ***Event-Transition Graph****. Interaction frequencies required to predict the population scale behavior as the asymptotic behavior of an accumulation multiplicative law over a Markov chain. Estimation by local searches in the space of Markov chains consistent with the observed dynamics and whose asymptotic behavior is consistent with quantitative observations at the population scale. Edge thickness reflects their sensitivity in the search space. It allows to* ***predict*** *the* Cya *protein concentration (red curve) which fits with observations. Additionally, literature evidences that high sensitivity ETG transitions correspond to key interaction in E. Coli response to nutritional stress.*

3.3. Grammatical inference and highly expressive structures

Our main field of expertise in machine learning concerns grammatical models with a strong expertise in finite state automata learning. By introducing a similar fragment merging heuristic approach, we have proposed an algorithm that learns successfully automata modeling families of (non homologous) functional families of proteins [3], leading to a tool named Protomata-learner. As an example, this tools allows us to properly model the function of the protein family TNF, which is impossible with other existing probabilistic-based approach (see Fig. 3). It was also applied to model families of proteins in cyanobacteria [2]. Our future goal

is to further demonstrate the relevance of formal language modelling by addressing the question of enzyme prediction, from their genomic or protein sequences, aiming at better sensitivity and specificity. As enzyme-substrate interactions are very specific central relations for integrated genome/metabolome studies and are characterized by faint signatures, we shall rely on models for active sites involved in cellular regulation or catalysis mechanisms. This requires to build models gathering both structural and sequence information is order to describe (potentially nested or crossing) long-term dependencies such as contacts of amino-acids that are far in the sequence but close in the 3D protein folding. We wish to extend our expertise towards inferring Context-Free Grammars including the topological information coming from the structural characterization of active sites.

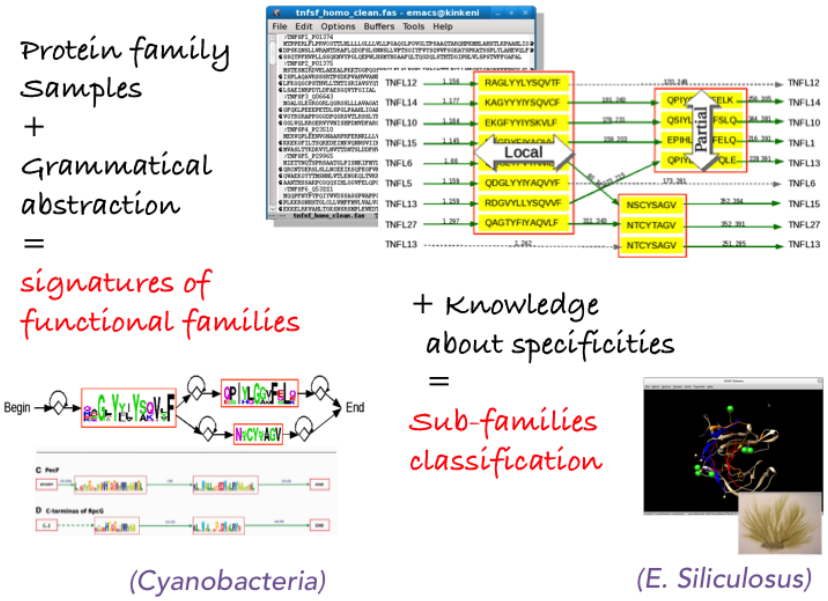
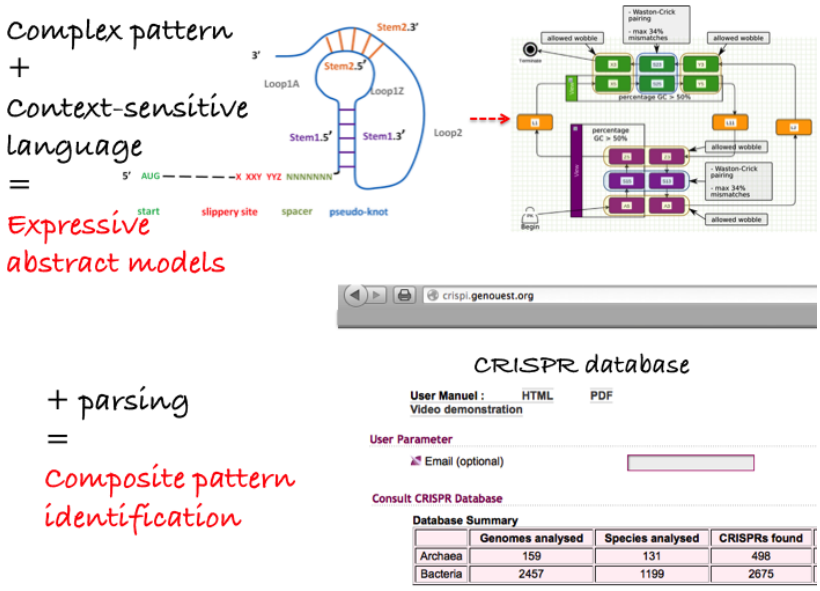


Figure 3. ***Protomata Learner workflow****. Starting from a set of protein sequences, a partial local alignment is computed and an automaton is inferred, which can be considered as a signature of the family of proteins. This allows searching for new members of the family [2]. Adding further information about the specific properties of proteins within the family allows to exhibit a refined classification.*

Using context-free grammars instead of regular patterns increases the complexity of parsing issues. Indeed, efficient parsing tools have been developed to identify patterns within genomes but most of them are restricted to simple regular patterns. Definite Clause Grammars (DCG), a particular form of logical context-free grammars have been used in various works to model DNA sequence features [54]. An extended formalism, String Variable Grammars (SVGs), introduces variables that can be associated to a string during a pattern search (see Fig. 4) [59], [58]. This increases the expressivity of the formalism towards midly context sensitive grammars. Thus, those grammars model not only DNA/RNA sequence features but also structural features such as repeats, palindromes, stem/loop or pseudo-knots. We have designed a tool, STAN (suffix-tree analyser) which makes it possible to search for a subset of SVG patterns in full chromosome sequences [7]. This tool was used for the recognition of transposable elements in *Arabidopsis thaliana* [60] or for the design of a CRISPR database [9]. See Figure 4 for illustration. Our goal is to extend the framework of STAN. Generally, a suitable language for the search of particular components in languages has to meet several needs : expressing existing structures in a compact way, using existing databases of motifs, helping the description of interacting

components. In other words, the difficulty is to find a good tradeoff between expressivity and complexity to allow the specification of realistic models at genome scale. In this direction, we are working on Logol, a language and framework based on a systematic introduction of constraints on string variables.



	Genomes analysed	Species analysed	CRISPRs found
Archaea	159	131	498
Bacteria	2457	1199	2675

Figure 4. Graphical modeling of a pseudo-knot (RNA structure) based on the expressivity of String Variable Grammars used in the Logol framework. Combined with parsers, this leads to composite pattern identification such as CRISPR [56].

FLUMINANCE Project-Team

3. Research Program

3.1. Estimation of fluid characteristic features from images

The measurement of fluid representative features such as vector fields, potential functions or vorticity maps, enables physicists to have better understanding of experimental or geophysical fluid flows. Such measurements date back to one century and more but became an intensive subject of research since the emergence of correlation techniques [29] to track fluid movements in pairs of images of a particles laden fluid or by the way of clouds photometric pattern identification in meteorological images. In computer vision, the estimation of the projection of the apparent motion of a 3D scene onto the image plane, referred to in the literature as optical-flow, is an intensive subject of researches since the 80's and the seminal work of B. Horn and B. Schunk [42]. Unlike to dense optical flow estimators, the former approach provides techniques that supply only sparse velocity fields. These methods have demonstrated to be robust and to provide accurate measurements for flows seeded with particles. These restrictions and their inherent discrete local nature limit too much their use and prevent any evolutions of these techniques towards the devising of methods supplying physically consistent results and small scale velocity measurements. It does not authorize also the use of scalar images exploited in numerous situations to visualize flows (image showing the diffusion of a scalar such as dye, pollutant, light index refraction, flurocein,...). At the opposite, variational techniques enable in a well-established mathematical framework to estimate spatially continuous velocity fields, which should allow more properly to go towards the measurement of smaller motion scales. As these methods are defined through PDE's systems they allow quite naturally including as constraints kinematic properties or dynamic laws governing the observed fluid flows. Besides, within this framework it is also much easier to define characteristic features estimation procedures on the basis of physically grounded data model that describes the relation linking the observed luminance function and some state variables of the observed flow.

A substantial progress has been done in this direction with the design of dedicated dense estimation techniques to estimate dense fluid motion fields[4], [10], the setting up of tomographic techniques to carry out 3D velocity measurements [36], the inclusion of physical constraints to infer 3D motions or the design of dynamically consistent velocity measurements to provide coherent motion fields from time resolved fluid flow image sequences [9]. These progresses have brought further accuracy and an improved spatial resolution for a variety of applications ranging from experimental fluid mechanics to geophysical sciences. For a detailed review of these approaches see [7].

We believe that such approaches must be first enlarged to the wide variety of imaging modalities enabling the observation of fluid flows. This covers for instance, the systematic study of motion estimation for the different channels of meteorological satellites, but also of other experimental imaging tools such as Shadowgraphs, Background oriented Schlieren, Schlieren [49], diffusive scalar images, fluid holography [50], or Laser Induced Fluorimetry. All these modalities offer the possibility to visualize time resolved sequences of the flow. The velocity measurement processes available to date for that kind of images suffer from a lack of physical relevancy to keep up with the increasing amount of fine and coherent information provided by the images. We think, and have begun to prove, that a significant step forward can be taken by providing new tools based on sound data models and adapted regularization functional, both built on physical grounds.

Additional difficulties arise when considering the necessity to go towards 3D measurements and 3D volumetric reconstruction of the observed flows (e.g., the tomographic PIV paradigm). First, unlike in the standard setup, the 2D images captured by the experimentalists only provide a partial information about the structure of the particles transported by the fluid. As a matter of fact, inverse problems have to be solved in order to recover this crucial information. Secondly, another issue stands in the increase of the underdetermination of the problem, that is the important decrease of the ratio between the number of observations and the total number of unknowns. In particular, this point asks for methodologies able to gather and exploit observations

captured at different time instants. Finally, the dimensions of the problem (that is, the number of unknown) dramatically increase with the transition from the 2D to the 3D paradigm. This leads, as a by-product, to a significant amplification of the computational burden and requires the conception of efficient algorithms, exhibiting a reasonable scaling with the problem dimensions.

The first problem can be addressed by resorting to state-of-the-art methodologies pertaining to sparse representations. These techniques consist in identifying the solution of an inverse problem with the most “zero" components which, in the case of the tomographic PIV, turns out to be a physically relevant option. Hence, the design of sparse representation algorithms and the study of their conditions of success constitute an important research topic of the group. On the other hand, we believe that the dramatic increase of the under-determination appearing in the 3D setup can be tackled by combining tomographic reconstruction of several planar views of the flow with data assimilation techniques. These techniques enable to couple a dynamical model with incomplete observations of the flow. Each applicative situation under concern defines its proper required scale of measurement and a scale for the dynamical model. For instance, for control or monitoring purposes, very rapid techniques are needed whereas for analysis purpose the priority is to get accurate measurements of the smallest motion scales as possible. These two extreme cases imply the use of different models but also of different algorithmic techniques. Recursive techniques and large scale representation of the flow are relevant for the first case whereas batch techniques relying on the whole set of data available and models refined down to small scales have to be used for the latter case.

The question of the scale of the velocity measurement is also an open question that must be studied carefully. Actually, no scale considerations are taken into account in the estimation schemes. It is more or less abusively assumed that the measurements supplied have a subpixel accuracy, which is obviously erroneous due to implicit smoothness assumptions made either in correlation techniques or in variational estimation techniques. We are convinced that to go towards the measurement of the smaller scales of the flow it is necessary to introduce some turbulence or uncertainty subgrid modeling within the estimation scheme and also to devise alternative regularization schemes that fit well with phenomenological statistical descriptions of turbulence described by the velocity increments moments. As a by product such schemes should offer the possibility to have a direct characterization, from image sequences, of the flow turbulent regions in term of vortex tube, area of pure straining, or vortex sheet. This philosophy should allow us to elaborate methods enabling the estimation of relevant characteristics of the turbulence like second-order structure functions, mean energy dissipation rate, turbulent viscosity coefficient, or dissipative scales.

We are planning to study these questions for a wide variety of application domains ranging from experimental fluid mechanics to geophysical sciences. We believe there are specific needs in different application domains that require clearly identified developments and modeling. Let us for instance mention meteorology and oceanography which both involve very specific dynamical modeling but also micro-fluidic applications or bio-fluid applications that are ruled by other types of dynamics.

3.2. Data assimilation and Tracking of characteristic fluid features

Real flows have an extent of complexity, even in carefully controlled experimental conditions, which prevents any set of sensors from providing enough information to describe them completely. Even with the highest levels of accuracy, space-time coverage and grid refinement, there will always remain at least a lack of resolution and some missing input about the actual boundary conditions. This is obviously true for the complex flows encountered in industrial and natural conditions, but remains also an obstacle even for standard academic flows thoroughly investigated in research conditions.

This unavoidable deficiency of the experimental techniques is nevertheless more and more compensated by numerical simulations. The parallel advances in sensors, acquisition, treatment and computer efficiency allow the mixing of experimental and simulated data produced at compatible scales in space and time. The inclusion of dynamical models as constraints of the data analysis process brings a guaranty of coherency based on fundamental equations known to correctly represent the dynamics of the flow (e.g. Navier Stokes equations) [3], [5].

Conversely, the injection of experimental data into simulations ensures some fitting of the model with reality. When used with the correct level of expertise to calibrate the models at the relevant scales, regarding data validity and the targeted representation scale, this collaboration represents a powerful tool for the analysis and reconstruction of the flows. Automated back and forth sequencing between data integration and calculations have to be elaborated for the different types of flows with a correct adjustment of the observed and modeled scales. This appears more and more feasible when considering the sensitivity, the space resolution and above all the time resolution that the imaging sensors are reaching now.

That becomes particularly true, for instance, for satellite imaging, the foreseeable advances of which will soon give the right complement to the progresses in atmospheric and ocean modeling to dramatically improve the analysis and predictions of physical states and streams for weather and environment monitoring. In that domain, there is a particular interest in being able to combine image data, models and in-situ measurements, as high densities of data supplied by meteorological stations are available only for limited regions of the world, typically Europe and USA, while Africa, or the south hemisphere lack of refined and frequent *in situ* measurements. Moreover, we believe that such an approach can favor great advances in the analysis and prediction of complex flows interactions like those encountered in sea-atmosphere interactions, dispersion of polluting agents in seas and rivers, etc. In other domains we believe that image data and dynamical models coupling may bring interesting solutions for the analysis of complex phenomena which involve multi-phasic flows, interaction between fluid and structures, and the general case of flows with complex unknown border conditions.

The coupling approach can be extended outside the fluidics domain to complex dynamics that can be modeled either from physical laws or from learning strategies based on the observation of previous events [1]. This concerns for instance forest combustion, the analysis of the biosphere evolution, the observation and prediction of the melting of pack ice, the evolution of sea ice, the study of the consequences of human activity like deforestation, city growing, landscape and farming evolution, etc. All these phenomena are nowadays rapidly evolving due to global warming. The measurement of their evolution is a major societal interest for analysis purpose or risk monitoring and prevention.

To enable data and models coupling to achieve its potential, some difficulties have to be tackled. It is in particular important to outline the fact that the coupling of dynamical models and image data are far from being straightforward. The first difficulty is related to the space of the physical model. As a matter of fact, physical models describe generally the phenomenon evolution in a 3D Cartesian space whereas images provides generally only 2D tomographic views or projections of the 3D space on the 2D image plane. Furthermore, these views are sometimes incomplete because of partial occlusions and the relations between the model state variables and the image intensity function are otherwise often intricate and only partially known. Besides, the dynamical model and the image data may be related to spatio-temporal scale spaces of very different natures which increases the complexity of an eventual multiscale coupling. As a consequence of these difficulties, it is necessary generally to define simpler dynamical models in order to assimilate image data. This redefinition can be done for instance on an uncertainty analysis basis, through physical considerations or by the way of data based empirical specifications. Such modeling comes to define inexact evolution laws and leads to the handling of stochastic dynamical models. The necessity to make use and define sound approximate models, the dimension of the state variables of interest and the complex relations linking the state variables and the intensity function, together with the potential applications described earlier constitute very stimulating issues for the design of efficient data-model coupling techniques based on image sequences.

On top of the problems mentioned above, the models exploited in assimilation techniques often suffer from some uncertainties on the parameters which define them. Hence, a new emerging field of research focuses on the characterization of the set of achievable solutions as a function of these uncertainties. This sort of characterization indeed turns out to be crucial for the relevant analysis of any simulation outputs or the correct interpretation of operational forecasting schemes. In this context, the tools provided by the Bayesian theory play a crucial role since they encompass a variety of methodologies to model and process uncertainty. As a consequence, the Bayesian paradigm has already been present in many contributions of the Fluminance group

in the last years and will remain a cornerstone of the new methodologies investigated by the team in the domain of uncertainty characterization.

This wide theme of research problems is a central topic in our research group. As a matter of fact, such a coupling may rely on adequate instantaneous motion descriptors extracted with the help of the techniques studied in the first research axis of the FLUMINANCE group. In the same time, this coupling is also essential with respect to visual flow control studies explored in the third theme. The coupling between a dynamics and data, designated in the literature as a Data Assimilation issue, can be either conducted with optimal control techniques [44], [45] or through stochastic filtering approaches [37], [40]. These two frameworks have their own advantages and deficiencies. We rely indifferently on both approaches.

3.3. Optimization and control of fluid flows with visual servoing

Fluid flow control is a recent and active research domain. A significant part of the work carried out so far in that field has been dedicated to the control of the transition from laminarity to turbulence. Delaying, accelerating or modifying this transition is of great economical interest for industrial applications. For instance, it has been shown that for an aircraft, a drag reduction can be obtained while enhancing the lift, leading consequently to limit fuel consumption. In contrast, in other application domains such as industrial chemistry, turbulence phenomena are encouraged to improve heat exchange, increase the mixing of chemical components and enhance chemical reactions. Similarly, in military and civilians applications where combustion is involved, the control of mixing by means of turbulence handling rouses a great interest, for example to limit infra-red signatures of fighter aircraft.

Flow control can be achieved in two different ways: passive or active control. Passive control provides a permanent action on a system. Most often it consists in optimizing shapes or in choosing suitable surfacing (see for example [33] where longitudinal riblets are used to reduce the drag caused by turbulence). The main problem with such an approach is that the control is, of course, inoperative when the system changes. Conversely, in active control the action is time varying and adapted to the current system's state. This approach requires an external energy to act on the system through actuators enabling a forcing on the flow through for instance blowing and suction actions [52], [39]. A closed-loop problem can be formulated as an optimal control issue where a control law minimizing an objective cost function (minimization of the drag, minimization of the actuators power, etc.) must be applied to the actuators [30]. Most of the works of the literature indeed comes back to open-loop control approaches [47], [41], [46] or to forcing approaches [38] with control laws acting without any feedback information on the flow actual state. In order for these methods to be operative, the model used to derive the control law must describe as accurately as possible the flow and all the eventual perturbations of the surrounding environment, which is very unlikely in real situations. In addition, as such approaches rely on a perfect model, a high computational costs is usually required. This inescapable pitfall has motivated a strong interest on model reduction. Their key advantage being that they can be specified empirically from the data and represent quite accurately, with only few modes, complex flows' dynamics. This motivates an important research axis in the Fluminance group.

Another important part of the works conducted in Fluminance concerns the study of closed-loop approaches, for which the convergence of the system to a target state is ensured even in the presence of errors (related either to the flow model, the actuators, or the sensors) [35]. However, designing a closed loop control law requires the use of sensors that are both non-intrusive, accurate and adapted to the time and spacial scales of the phenomenon to monitor. Such sensors are unfortunately hardly available in the context of flow control. The only sensors currently used are wall sensors located in a limited set of measurement points [31], [34]. The difficulty is then to reconstruct the entire state of the controlled system from a model based only on the few measurements available on the walls [43]. Instead of relying on sparse measurements, we propose to use denser features estimated from images. With the capabilities of up-to-date imaging sensors, we can expect an improved reconstruction of the flow (both in space and time) enabling the design of efficient image based control laws. This formulation is referred to as visual servoing control scheme.

Visual servoing is a widely used technique for robot control. It consists in using data provided by a vision sensor for controlling the motions of a robot [32]. This technique, historically embedded in the larger domain of sensor-based control [48], can be properly used to control complex robotic systems or, as we showed it recently, flows [51].

Classically, to achieve a visual servoing task, a set of visual features, $\mathbf{s}$, has to be selected from visual measurements, $\mathbf{m}$, extracted from a current image. A control law is then designed so that these visual features reach a desired value, $\mathbf{s}^*$, related to the target state of the system. The control principle consists in regulating to zero the error vector: $\mathbf{e} = \mathbf{s} - \mathbf{s}^*$. To build the control law, the knowledge of the so-called *interaction matrix* $\mathbf{L_s}$ is usually required. This matrix links the time variation of $\mathbf{s}$ to the signal command $\mathbf{u}$. However, computing this matrix in the context of flow control is far more complex than in the case of robot control as flows are associated to chaotic nonlinear systems living in infinite dimensional spaces. As such, it is possible to formalize the model through a Galerkin projection in terms of an ODE system for which classical control laws can be applied. It is also possible to express the system with finite difference approximations and to use discrete time control algorithms amenable to modern micro-controllers. Alternatively, one may develop control methods directly on the infinite dimensional system and then finally discretize the resulting process for implementation purpose. Each approach has its own advantages and drawbacks. For the first two, known control methods can be used at the expense of a great sensibility to space discretization. The last one is less sensitive to discretization errors but more difficult to set up. These practical issues and their related theoretical difficulties make this study a very interesting field of research.

GENSCALE Project-Team

3. Research Program

3.1. Introduction

To tackle challenges brought by the processing of huge amount of genomic data, the main strategy of GenScale is to merge the following computer science expertise:

- Data structure;
- Combinatorial optimization;
- Parallelism.

3.2. Data structure

To face the genomic data tsunami, the design of efficient algorithms involves the optimization of memory footprints. A key point is the design of innovative data structures to represent large genomic datasets into computer memories. Today's limitations come from their size, their construction time, or their centralized (sequential) access. Random accesses to large data structures poorly exploit the sophisticated processor cache memory system. New data structures including compression techniques, probabilistic filters, approximate string matching, or techniques to improve spatial/temporal memory access are developed [3].

3.3. Combinatorial optimization

For wide genome analysis, Next Generation Sequencing (NGS) data processing or protein structure applications, the main issue concerns the exploration of sets of data by time-consuming algorithms, with the aim of identifying solutions that are optimal in a predefined sense. In this context, speeding up such algorithms requires acting on many directions: (1) optimizing the search with efficient heuristics and advanced combinatorial optimization techniques [2], [5] or (2) targeting biological sub-problems to reduce the search space [7], [9]. Designing algorithms with adapted heuristics, and able to scale from protein (a few hundreds of amino acids) to full genome (millions to billions of nucleotides) is one of the competitive challenges addressed in the GenScale project.

3.4. Parallelism

The traditional parallelization approach, which consists in moving from a sequential to a parallel code, must be transformed into a direct design and implementation of high performance parallel software. All levels of parallelism (vector instructions, multi-cores, many-cores, clusters, grid, clouds) need to be exploited in order to extract the maximum computing power from current hardware resources [6], [8], [1]. An important specificity of GenScale is to systematically adopt a design approach where all levels of parallelism are potentially considered.

SAGE Project-Team

3. Research Program

3.1. Numerical algorithms and high performance computing

Linear algebra is at the kernel of most scientific applications, in particular in physical or chemical engineering. For example, steady-state flow simulations in porous media are discretized in space and lead to a large sparse linear system. The target size is 10^7 in 2D and 10^{10} in 3D. For transient models such as diffusion, the objective is to solve about 10^4 linear systems for each simulation. Memory requirements are of the order of Giga-bytes in 2D and Tera-bytes in 3D. CPU times are of the order of several hours to several days. Several methods and solvers exist for large sparse linear systems. They can be divided into three classes: direct, iterative or semi-iterative. Direct methods are highly efficient but require a large memory space and a rapidly increasing computational time. Iterative methods of Krylov type require less memory but need a scalable preconditioner to remain competitive. Iterative methods of multigrid type are efficient and scalable, used by themselves or as preconditioners, with a linear complexity for elliptic or parabolic problems but they are not so efficient for hyperbolic problems. Semi-iterative methods such as subdomain methods are hybrid direct/iterative methods which can be good tradeoffs. The convergence of iterative and semi-iterative methods and the accuracy of the results depend on the condition number which can blow up at large scale. The objectives are to analyze the complexity of these different methods, to accelerate convergence of iterative methods, to measure and improve the efficiency on parallel architectures, to define criteria of choice.

In geophysics, a main concern is to solve inverse problems in order to fit the measured data with the model. Generally, this amounts to solve a linear or nonlinear least-squares problem. Complex models are in general coupled multi-physics models. For example, reactive transport couples advection-diffusion with chemistry. Here, the mathematical model is a set of nonlinear Partial Differential Algebraic Equations. At each timestep of an implicit scheme, a large nonlinear system of equations arise. The challenge is to solve efficiently and accurately these large nonlinear systems.

Approximation in Krylov subspace is in the core of the team activity since it provides efficient iterative solvers for linear systems and eigenvalue problems as well. The later are encountered in many fields and they include the singular value problem which is especially useful when solving ill posed inverse problems.

3.2. Numerical models applied to hydrogeology and physics

The team Sage is strongly involved in numerical models for hydrogeology and physics. There are many scientific challenges in the area of groundwater simulations. This interdisciplinary research is very fruitful with cross-fertilizing subjects. For example, high performance simulations were very helpful for finding out the asymptotic behaviour of the plume of solute transported by advection-dispersion. Numerical models are necessary to understand flow transfer in fractured media.

The team develops stochastic models for groundware simulations. Numerical models must then include Uncertainty Quantification methods, spatial and time discretization. Then, the discrete problems must be solved with efficient algorithms. The team develops parallel algorithms for complex numerical simulations and conducts performance analysis. Another challenge is to run multiparametric simulations. They can be multiple samples of a non intrusive Uncertainty Quantification method, or multiple samples of a stochastic method for inverse problems, or multiple samples for studying the sensitivity to a given model parameter. Thus these simulations are more or less independent and are well-suited to grid computing but each simulation requires powerful CPU and memory resources.

A strong commitment of the team is to develop the scientific software platform H2OLab for numerical simulations in heterogeneous hydrogeology.

SERPICO Project-Team

3. Research Program

3.1. Statistics and algorithms for computational microscopy

Many live-cell fluorescence imaging experiments are limited in time to prevent phototoxicity and photobleaching. The amount of light and time required to observe entire cell divisions can generate biological artifacts. In order to produce images compatible with the dynamic processes in living cells as seen in video-microscopy, we study the potential of denoising, superresolution, tracking, and motion analysis methods in the Bayesian and the robust statistics framework to extract information and to improve image resolution while preserving cell integrity.

In this area, we have already demonstrated that image denoising allows images to be taken more frequently or over a longer period of time [5]. The major advantage is to preserve cell integrity over time since spatio-temporal information can be restored using computational methods [6], [2], [7], [4]. This idea has been successfully applied to wide-field, spinning-disk confocal microscopy [1], TIRF [29], fast live imaging and 3D-PALM using the OMX system in collaboration with J. Sedat and M. Gustafsson at UCSF [5]. The corresponding ND-SAFIR denoiser software (see Section 5.1) has been licensed to a large set of laboratories over the world. New information restoration and image denoising methods are currently investigated to make SIM imaging compatible with the imaging of molecular dynamics in live cells. Unlike other optical sub-diffraction limited techniques (e.g. STED [43], PALM [31]) SIM has the strong advantage of versatility when considering the photo-physical properties of the fluorescent probes [40]. Such developments are also required to be compatible with "high-throughput microscopy" since several hundreds of cells are observed at the same time and the exposure times are typically reduced.

3.2. From image data to descriptors: dynamic analysis and trajectory computation

3.2.1. Motion analysis and tracking

The main challenge is to detect and track xFP tags with high precision in movies representing several Giga-Bytes of image data. The data are most often collected and processed automatically to generate information on partial or complete trajectories. Accordingly, we address both the methodological and computational issues involved in object detection and multiple objects tracking in order to better quantify motion in cell biology. Classical tracking methods have limitations as the number of objects and clutter increase. It is necessary to correctly associate measurements with tracked objects, i.e. to solve the difficult data association problem [52]. Data association even combined with sophisticated particle filtering techniques [55] or matching techniques [53] is problematic when tracking several hundreds of similar objects with variable velocities. Developing new optical flow and robust tracking methods and models in this area is then very stimulating since the problems we have to solve are really challenging and new for applied mathematics. In motion analysis, the goal is to formulate the problem of optical flow estimations in ways that take physical causes of brightness constancy violations into account [36], [41]. The interpretation of computed flow fields enables to provide spatio-temporal signatures of particular dynamic processes (e.g. Brownian and directed motion) and could help to complete the traffic modelling.

3.2.2. Event detection and motion classification

Protein complexes in living cells undergo multiple states of local concentration or dissociation, sometimes associated with diffusion processes. These events can be observed at the plasma membrane with TIRF microscopy. The difficulty arises when it becomes necessary to distinguish continuous motions due to trafficking from sudden events due to molecule concentrations or their dissociations. Typically, plasma membrane vesicle docking, membrane coat constitution or vesicle endocytosis are related to these issues.

Several approaches can be considered for the automatic detection of appearing and vanishing particles (or spots) in wide-field and TIRF microscopy images. Ideally this could be performed by tracking all the vesicles contained in the cell [55], [39]. Among the methods proposed to detect particles in microscopy images [57], [54], none is dedicated to the detection of a small number of particles appearing or disappearing suddenly between two time steps. Our way of handling small blob appearances/dis-appearances originates from the observation that two successive images are redundant and that occlusions correspond to blobs in one image which cannot be reconstructed from the other image [1] (see also [34]). Furthermore, recognizing dynamic protein behaviors in live cell fluorescence microscopy is of paramount importance to understand cell mechanisms. In our studies, it is challenging to classify intermingled dynamics of vesicular movements, docking/tethering, and ultimately, plasma membrane fusion of vesicles that leads to membrane diffusion or exocytosis of cargo proteins. Our aim is then to model, detect, estimate and classify subcellular dynamic events in TIRF microscopy image sequences. We investigate methods that exploits space-time information extracted from a couple of successive images to classify several types of motion (directed, diffusive (or Brownian) and confined motion) or compound motion.

3.3. From models to image data: simulation and modelling of membrane transport

Mathematical biology is a field in expansion, which has evolved into various branches and paradigms to address problems at various scales ranging from ecology to molecular structures. Nowadays, system biology [44], [59] aims at modelling systems as a whole in an integrative perspective instead of focusing on independent biophysical processes. One of the goals of these approaches is the cell in silico as investigated at Harvard Medical School (http://vcp.med.harvard.edu/) or the VCell of the University of Connecticut Health Center (http://www.nrcam.uchc.edu/). Previous simulation-based methods have been investigated to explain the spatial organization of microtubules [47] but the method is not integrative and a single scale is used to describe the visual patterns. In this line of work, we propose several contributions to combine imaging, traffic and membrane transport modelling in cell biology.

In this area, we focus on the analysis of transport intermediates (vesicles) that deliver cellular components to appropriate places within cells. We have already investigated the concept of Network Tomography (NT) [58] mainly developed for internet traffic estimation. The idea is to determine mean traffic intensities based on statistics accumulated over a period of time. The measurements are usually the number of vesicles detected at each destination region receiver. The NT concept has been investigated also for simulation [3] since it can be used to statistically mimic the contents of real traffic image sequences. In the future, we plan to incorporate more prior knowledge on dynamics to improve representation. An important challenge is to correlate stochastic, dynamical, one-dimensional *in silico* models studied at the nano-scale in biophysics, to 3D images acquired in vivo at the scale of few hundred nanometers. A difficulty is related to the scale change and statistical aggregation problems (in time and space) have to be handled.

VISAGES Project-Team

3. Research Program

3.1. Research Program

The scientific foundations of our team concern the development of new processing algorithms in the field of medical image computing : image fusion (registration and visualization), image segmentation and analysis, management of image related information. Since this is a very large domain, which can endorse numerous types of application; for seek of efficiency, the purpose of our methodological work primarily focuses on clinical aspects and for the most part on head and neck related diseases. In addition, we emphasize our research efforts on the neuroimaging domain. Concerning the scientific foundations, we have pushed our research efforts:

- In the field of image fusion and image registration (rigid and deformable transformations) with a special emphasis on new challenging registration issues, especially when statistical approaches based on joint histogram cannot be used or when the registration stage has to cope with loss or appearance of material (like in surgery or in tumor imaging for instance).
- In the field of image analysis and statistical modeling with a new focus on image feature and group analysis problems. A special attention was also to develop advanced frameworks for the construction of atlases and for automatic and supervised labeling of brain structures.
- In the field of image segmentation and structure recognition, with a special emphasis on the difficult problems of *i*) image restoration for new imaging sequences (new Magnetic Resonance Imaging protocols, 3D ultrasound sequences...), and *ii*) structure segmentation and labelling based on shape, multimodal and statistical information.
- Following the Neurobase national project where we had a leading role, we wanted to enhance the development of distributed and heterogeneous medical image processing systems.

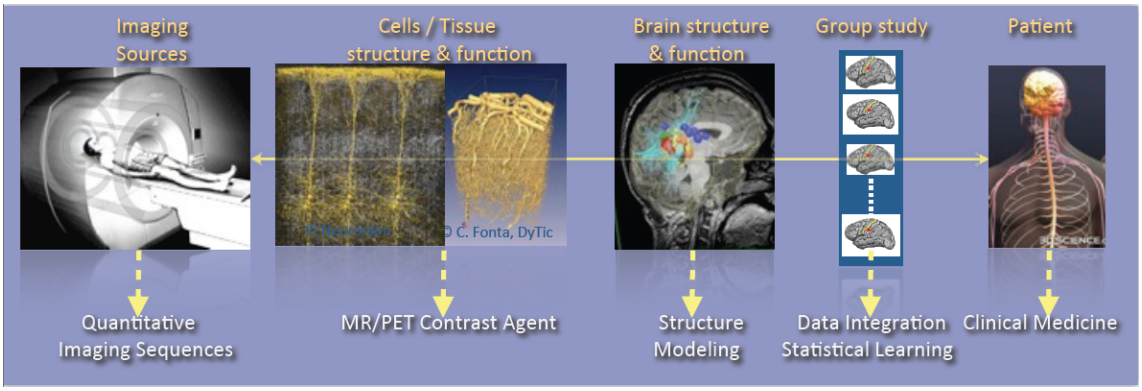


Figure 1. The major overall scientific foundation of the team concerns the integration of data from the Imaging source to the patient at different scales : from the cellular or molecular level describing the structure and function, to the functional and structural level of brain structures and regions, to the population level for the modelling of group patterns and the learning of group or individual imaging markers

As shown in figure 1 , research activities of the VISAGES U746 team are tightly coupling observations and models through integration of clinical and multi-scale data, phenotypes (cellular, molecular or structural patterns). We work on personalized models of central nervous system organs and pathologies, and intend to confront these models to clinical investigation studies for quantitative diagnosis, prevention of diseases, therapy planning and validation. These approaches are developed in a translational framework where the data integration process to build the models inherits from specific clinical studies, and where the models are assessed on prospective clinical trials for diagnosis and therapy planning. All of this research activity is conducted in tight links with the Neurinfo imaging platform environments and the engineering staff of the platform. In this context, some of our major challenges in this domain concern:

- The elaboration of new descriptors to study the brain structure and function (e.g. variation of brain perfusion with and without contrast agent, evolution in shape and size of an anatomical structure in relation with normal, pathological or functional patterns, computation of asymmetries from shapes and volumes).
- The integration of additional spatio-temporal imaging sequences covering a larger range of observation, from the molecular level to the organ through the cell (Arterial Spin Labeling, diffusion MRI, MR relaxometry, MR cell labeling imaging, PET molecular imaging, ...). This includes the elaboration of new image descriptors coming from spatio-temporal quantitative or contrast-enhanced MRI.
- The creation of computational models through data fusion of molecular, cellular, structural and functional image descriptors from group studies of normal and/or pathological subjects.
- The evaluation of these models on acute pathologies especially for the study of degenerative, psychiatric or developmental brain diseases (e.g. Multiple Sclerosis, Epilepsy, Parkinson, Dementia, Strokes, Depression, Schizophrenia, ...) in a translational framework.

In terms of methodological developments, we are particularly working on statistical methods for multidimensional image analysis, and feature selection and discovery, which includes:

- The development of specific shape and appearance models, construction of atlases better adapted to a patient or a group of patients in order to better characterize the pathology;
- The development of advanced segmentation and modeling methods dealing with longitudinal and multidimensional data (vector or tensor fields), especially with the integration of new prior models to control the integration of multiscale data and aggregation of models;
- The development of new models and probabilistic methods to create water diffusion maps from MRI;
- The integration of machine learning procedures for classification and labeling of multidimensional features (from scalar to tensor fields and/or geometric features): pattern and rule inference and knowledge extraction are key techniques to help in the elaboration of knowledge in the complex domains we address;
- The development of new dimensionality reduction techniques for problems with massive data, which includes dictionary learning for sparse model discovery. Efficient techniques have still to be developed to properly extract from a raw mass of images derived data that are easier to analyze.

ASAP Project-Team

3. Research Program

3.1. Distributed computing

Distributed computing was born in the late seventies when people started taking into account the intrinsic characteristics of physically distributed systems. The field then emerged as a specialized research area distinct from networks, operating systems and parallelism. Its birth certificate is usually considered as the publication in 1978 of Lamport's most celebrated paper "*Time, clocks and the ordering of events in a distributed system*" [55] (that paper was awarded the Dijkstra Prize in 2000). Since then, several high-level journals and (mainly ACM and IEEE) conferences have been devoted to distributed computing. The distributed systems area has continuously been evolving, following the progresses of all the above-mentioned areas such as networks, computing architecture, operating systems.

The last decade has witnessed significant changes in the area of distributed computing. This has been acknowledged by the creation of several conferences such as NSDI and IEEE P2P. The NSDI conference is an attempt to reassemble the networking and system communities while the IEEE P2P conference was created to be a forum specialized in peer-to-peer systems. At the same time, the EuroSys conference originated as an initiative of the European Chapter of the ACM SIGOPS to gather the system community in Europe.

3.2. Theory of distributed systems

Finding models for distributed computations prone to asynchrony and failures has received a lot of attention. A lot of research in this domain focuses on what can be computed in such models, and, when a problem can be solved, what are its best solutions in terms of relevant cost criteria. An important part of that research is focused on distributed computability: what can be computed when failure detectors are combined with conditions on process input values for example. Another part is devoted to model equivalence. What can be computed with a given class of failure detectors? Which synchronization primitives is a given failure class equivalent to? These are among the main topics addressed in the leading distributed computing community. A second fundamental issue related to distributed models, is the definition of appropriate models suited to dynamic systems. Up to now, the researchers in that area consider that nodes can enter and leave the system, but do not provide a simple characterization, based on properties of computation instead of description of possible behaviors [56], [50], [51]. This shows that finding dynamic distributed computing models is today a "Holy Grail", whose discovery would allow a better understanding of the essential nature of dynamic systems.

3.3. Peer-to-peer overlay networks

A standard distributed system today is related to thousands or even millions of computing entities scattered all over the world and dealing with a huge amount of data. This major shift in scalability requirements has lead to the emergence of novel computing paradigms. In particular, the peer-to-peer communication paradigm imposed itself as the prevalent model to cope with the requirements of large scale distributed systems. Peer-to-peer systems rely on a symmetric communication model where peers are potentially both clients and servers. They are fully decentralized, thus avoiding the bottleneck imposed by the presence of servers in traditional systems. They are highly resilient to peers arrivals and departures. Finally, individual peer behavior is based on a local knowledge of the system and yet the system converges toward global properties.

A peer-to-peer overlay network logically connects peers on top of IP. Two main classes of such overlays dominate, structured and unstructured. The differences relate to the choice of the neighbors in the overlay, and the presence of an underlying naming structure. Overlay networks represent the main approach to build large-scale distributed systems that we retained. An overlay network forms a logical structure connecting participating entities on top of the physical network, be it IP or a wireless network. Such an overlay might form a structured overlay network [57], [58], [59] following a specific topology or an unstructured network [54], [60] where participating entities are connected in a random or pseudo-random fashion. In between, lie weakly structured peer-to-peer overlays where nodes are linked depending on a proximity measure providing more flexibility than structured overlays and better performance than fully unstructured ones. Proximity-aware overlays connect participating entities so that they are connected to close neighbors according to a given proximity metric reflecting some degree of affinity (computation, interest, etc.) between peers. We extensively use this approach to provide algorithmic foundations of large-scale dynamic systems.

3.4. Epidemic protocols

Epidemic algorithms, also called gossip-based algorithms [53], [52], constitute a fundamental topic in our research. In the context of distributed systems, epidemic protocols are mainly used to create overlay networks and to ensure a reliable information dissemination in a large-scale distributed system. The principle underlying technique, in analogy with the spread of a rumor among humans via gossiping, is that participating entities continuously exchange information about the system in order to spread it gradually and reliably. Epidemic algorithms have proved efficient to build and maintain large-scale distributed systems in the context of many applications such as broadcasting [52], monitoring, resource management, search, and more generally in building unstructured peer-to-peer networks.

3.5. Malicious process behaviors

When assuming that processes fail by simply crashing, bounds on resiliency (maximum number of processes that may crash), number of exchanged messages, number of communication steps, etc. either in synchronous and augmented asynchronous systems (recall that in purely asynchronous systems some problems are impossible to solve) are known. If processes can exhibit malicious behaviors, these bounds are seldom the same. Sometimes, it is even necessary to change the specification of the problem. For example, the consensus problem for correct processes does not make sense if some processes can exhibit a Byzantine behavior and thus propose an arbitrary value. In this case, the validity property of consensus, which is normally "a decided value is a proposed value", must be changed to "if all correct processes propose the same value then only this value can be decided." Moreover, the resilience bound of less than half of faulty processes is at least lowered to "less than a third of Byzantine processes." These are some of the aspects that underlie our studies in the context of the classical model of distributed systems, in peer-to-peer systems and in sensor networks.

3.6. Online social networks and recommender systems

Social Networks have rapidly become a fundamental component of today's distributed applications. Web 2.0 applications have dramatically changed the way users interact with the Internet and with each other. The number of users of websites like Flickr, Delicious, Facebook, or MySpace is constantly growing, leading to significant technical challenges. On the one hand, these websites are called to handle enormous amounts of data. On the other hand, news continue to report the emergence of privacy threats to the personal data of social-network users. Our research aims to exploit our expertise in distributed systems to lead to a new generation of scalable, privacy-preserving, social applications.

We also investigate approaches to build implicit social networks, connecting users sharing similar interests. At the heart of the building of such similarity graphs lie k-nearest neighbor (KNN) algorithms. Our research in this area is to design and implement efficient KNN algorithms able to cope with a huge volume of data as well as a high level of dynamism. We investigate the use of such similarity graphs to build highly scalable infrastructures for recommendation systems.

ASCOLA Project-Team

3. Research Program

3.1. Overview

Since we mainly work on new concepts for the language-based definition and implementation of complex software systems, we first briefly introduce some basic notions and problems of software components (understood in a broad sense, that is, including modules, objects, architecture description languages and services), aspects, and domain-specific languages. We conclude by presenting the main issues related to distribution and concurrency, in particular related to capacity planning issues that are relevant to our work.

3.2. Software Composition

Modules and services. The idea that building *software components*, i.e., composable prefabricated and parameterized software parts, was key to create an effective software industry was realized very early [64]. At that time, the scope of a component was limited to a single procedure. In the seventies, the growing complexity of software made it necessary to consider a new level of structuring and programming and led to the notions of information hiding, *modules*, and module interconnection languages [71], [49]. Information hiding promotes a black-box model of program development whereby a module implementation, basically a collection of procedures, is strongly encapsulated behind an interface. This makes it possible to guarantee logical invariant *properties* of the data managed by the procedures and, more generally, makes *modular reasoning* possible.

In the context of today's Internet-based information society, components and modules have given rise to *software services* whose compositions are governed by explicit *orchestration or choreography* specifications that support notions of global properties of a service-oriented architecture. These horizontal compositions have, however, to be frequently adapted dynamically. Dynamic adaptations, in particular in the context of software evolution processes, often conflict with a black-box composition model either because of the need for invasive modifications, for instance, in order to optimize resource utilization or modifications to the vertical compositions implementing the high-level services.

Object-Oriented Programming. Classes and objects provide another kind of software component, which makes it necessary to distinguish between *component types* (classes) and *component instances* (objects). Indeed, unlike modules, objects can be created dynamically. Although it is also possible to talk about classes in terms of interfaces and implementations, the encapsulation provided by classes is not as strong as the one provided by modules. This is because, through the use of inheritance, object-oriented languages put the emphasis on *incremental programming* to the detriment of modular programming. This introduces a white-box model of software development and more flexibility is traded for safety as demonstrated by the *fragile base class* issue [67].

Architecture Description Languages. The advent of distributed applications made it necessary to consider more sophisticated connections between the various building blocks of a system. The *software architecture* [75] of a software system describes the system as a composition of *components* and *connectors*, where the connectors capture the *interaction protocols* between the components [40]. It also describes the rationale behind such a given architecture, linking the properties required from the system to its implementation. *Architecture Description Languages* (ADLs) are languages that support architecture-based development [65]. A number of these languages make it possible to generate executable systems from architectural descriptions, provided implementations for the primitive components are available. However, guaranteeing that the implementation conforms to the architecture is an issue.

Protocols. Today, protocols constitute a frequently used means to precisely define, implement, and analyze contracts, notably concerning communication and security properties, between two or more hardware or software entities. They have been used to define interactions between communication layers, security properties of distributed communications, interactions between objects and components, and business processes.

Object interactions [69], component interactions [81], [73] and service orchestrations [50] are most frequently expressed in terms of *regular interaction protocols* that enable basic properties, such as compatibility, substitutability, and deadlocks between components to be defined in terms of basic operations and closure properties of finite-state automata. Furthermore, such properties may be analyzed automatically using, e.g., model checking techniques [47], [56].

However, the limited expressive power of regular languages has led to a number of approaches using more expressive *non-regular* interaction protocols that often provide distribution-specific abstractions, e.g., session types [58], or context-free or turing-complete expressiveness [74], [45]. While these protocol types allow conformance between components to be defined (e.g., using unbounded counters), property verification can only be performed manually or semi-automatically.

3.3. Programming languages for advanced modularization

The main driving force for the structuring means, such as components and modules, is the quest for clean *separation of concerns* [51] on the architectural and programming levels. It has, however, early been noted that concern separation in the presence of crosscutting functionalities requires specific language and implementation level support. Techniques of so-called *computational reflection*, for instance, Smith's 3-Lisp or Kiczales's CLOS meta-object protocol [76], [61] as well as metaprogramming techniques have been developed to cope with this problem but proven unwieldy to use and not amenable to formalization and property analysis due to their generality. Methods and techniques from two fields have been particularly useful in addressing such advanced modularization problems: Aspect-Oriented Software Development as the field concerned with the systematic handling of modularization issues and domain-specific languages that provide declarative and efficient means for the definition of crosscutting functionalities.

Aspect-Oriented Software Development [60], [38] has emerged over the previous decade as the domain of systematic exploration of crosscutting concerns and corresponding support throughout the software development process. The corresponding research efforts have resulted, in particular, in the recognition of *crosscutting* as a fundamental problem of virtually any large-scale application, and the definition and implementation of a large number of aspect-oriented models and languages.

However, most current aspect-oriented models, notably AspectJ [59], rely on pointcuts and advice defined in terms of individual execution events. These models are subject to serious limitations concerning the modularization of crosscutting functionalities in distributed applications, the integration of aspects with other modularization mechanisms such as components, and the provision of correctness guarantees of the resulting AO applications. They do, in particular, only permit the manipulation of distributed applications on a per-host basis, that is, without direct expression of coordination properties relating different distributed entities [77]. Similarly, current approaches for the integration of aspects and (distributed) components do not directly express interaction properties between sets of components but rather seemingly unrelated modifications to individual components [48]. Finally, current formalizations of such aspect models are formulated in terms of low-level semantic abstractions (see, e.g., Wand's et al semantics for AspectJ [80]) and provide only limited support for the analysis of fundamental aspect properties.

Different approaches have been put forward to tackle these problems, in particular, in the context of so-called *stateful* or *history-based aspect languages* [52], [53], which provide pointcut and advice languages that directly express rich relationships between execution events. Such languages have been proposed to directly express coordination and synchronization issues of distributed and concurrent applications [70], [43], [55], provide more concise formal semantics for aspects and enable analysis of their properties [41], [54], [52], [39]. Furthermore, first approaches for the definition of *aspects over protocols* have been proposed, as well as over regular structures [52] and non-regular ones [79], [68], which are helpful for the modular definition and verification of protocols over crosscutting functionalities.

They represent, however, only first results and many important questions concerning these fundamental issues remain open, in particular, concerning the semantics foundations of AOP and the analysis and enforcement of correctness properties governing its, potentially highly invasive, modifications.

Domain-specific languages (DSLs) represent domain knowledge in terms of suitable basic language constructs and their compositions at the language level. By trading generality for abstraction, they enable complex relationships among domain concepts to be expressed concisely and their properties to be expressed and formally analyzed. DSLs have been applied to a large number of domains; they have been particularly popular in the domain of software generation and maintenance [66], [82].

Many modularization techniques and tasks can be naturally expressed by DSLs that are either specialized with respect to the type of modularization constructs, such as a specific brand of software component, or to the compositions that are admissible in the context of an application domain that is targeted by a modular implementation. Moreover, software development and evolution processes can frequently be expressed by transformations between applications implemented using different DSLs that represent an implementation at different abstraction levels or different parts of one application.

Functionalities that crosscut a component-based application, however, complicate such a DSL-based transformational software development process. Since such functionalities belong to another domain than that captured by the components, different DSLs should be composed. Such compositions (including their syntactic expression, semantics and property analysis) have only very partially been explored until now. Furthermore, restricted composition languages and many aspect languages that only match execution events of a specific domain (e.g., specific file accesses in the case of security functionality) and trigger only domain-specific actions clearly are quite similar to DSLs but remain to be explored.

3.4. Distribution and Concurrency

While ASCOLA does not investigate distribution and concurrency as research domains per se (but rather from a software engineering and modularization viewpoint), there are several specific problems and corresponding approaches in these domains that are directly related to its core interests that include the structuring and modularization of large-scale distributed infrastructures and applications. These problems include crosscutting functionalities of distributed and concurrent systems, support for the evolution of distributed software systems, and correctness guarantees for the resulting software systems.

Underlying our interest in these domains is the well-known observation that large-scale distributed applications are subject to *numerous crosscutting functionalities* (such as the transactional behavior in enterprise information systems, the implementation of security policies, and fault recovery strategies). These functionalities are typically partially encapsulated in distributed infrastructures and partially handled in an ad hoc manner by using infrastructure services at the application level. Support for a more principled approach to the development and evolution of distributed software systems in the presence of crosscutting functionalities has been investigated in the field of *open adaptable middleware* [44], [63]. Open middleware design exploits the concept of reflection to provide the desired level of configurability and openness. However, these approaches are subject to several fundamental problems. One important problem is their insufficient, framework-based support that only allows partial modularization of crosscutting functionalities.

There has been some *criticism* on the use of *AspectJ-like aspect models* (which middleware aspect models like that of JBoss AOP are an instance of) for the modularization of distribution and concurrency related concerns, in particular, for transaction concerns [62] and the modularization of the distribution concern itself [77]. Both criticisms are essentially grounded in AspectJ's inability to explicitly represent sophisticated relationships between execution events in a distributed system: such aspects therefore cannot capture the semantic relationships that are essential for the corresponding concerns. History-based aspects, as those proposed by the ASCOLA project-team provide a starting point that is not subject to this problem.

From a point of view of language design and implementation, aspect languages, as well as domain specific languages for distributed and concurrent environments share many characteristics with existing distributed languages: for instance, event monitoring is fundamental for pointcut matching, different synchronization strategies and strategies for code mobility [57] may be used in actions triggered by pointcuts. However, these relationships have only been explored to a small degree. Similarly, the formal semantics and formal properties of aspect languages have not been studied yet for the distributed case and only rudimentarily for the concurrent one [41], [55].

3.5. Security

Security properties and policies over complex service-oriented and standalone applications become ever more important in the context of asynchronous and decentralized communicating systems. Furthermore, they constitute prime examples of crosscutting functionalities that can only be modularized in highly insufficient ways with existing programming language and service models. Security properties and related properties, such as accountability properties, are therefore very frequently awkward to express and difficult to analyze and enforce (provided they can be made explicit in the first place).

Two main issues in this space are particularly problematic from a compositional point of view. First, information flow properties of programming languages, such as flow properties of Javascript [42], and service-based systems [46] are typically specially-tailored to specific properties, as well as difficult to express and analyze. Second, the enforcement of security properties and security policies, especially accountability-related properties [72], [78], is only supported using ad hoc means with rudimentary support for property verification.

The ASCOLA team has recently started to work on providing formal methods, language support and implementation techniques for the modular definition and implementation of information flow properties as well as policy enforcement in service-oriented systems as well as, mostly object-oriented, programming languages.

3.6. Capacity Planning for Large Scale Distributed System

Since the last decade, cloud computing has emerged as both a new economic model for software (provision) and as flexible tools for the management of computing capacity. Nowadays, the major cloud features have become part of the mainstream (virtualization, storage and software image management) and the big market players offer effective cloud-based solutions for resource pooling. It is now possible to deploy virtual infrastructures that involve virtual machines (VMs), middleware, applications, and networks in such a simple manner that a new problem has emerged over the last two years: VM sprawl (virtual machine proliferation) that consumes valuable computing, memory, storage and energy resources, thus menacing serious resource shortages. Scientific approaches that address VM sprawl are both based on classical administration techniques like the lifecycle management of a large number of VMs as well as the arbitration and the careful management of all resources consumed and provided by the hosting infrastructure (energy, power, computing, memory, network etc.).

The ASCOLA team investigates fundamental techniques for cloud computing and capacity planning, from infrastructures to the application level. Capacity planning is the process of planning for, analyzing, sizing, managing and optimizing capacity to satisfy demand in a timely manner and at a reasonable cost. Applied to distributed systems like clouds, a capacity planning solution must mainly provide the minimal set of resources necessary for the proper execution of the applications (i.e., to ensure service level agreement, SLA). The main challenges in this context are: scalability, fault tolerance and reactivity of the solution in a large-scale distributed system, the analysis and optimization of resources to minimize the cost (mainly costs related to the energy consumption of datacenters), as well as the profiling and adaptation of applications to ensure useful levels of quality of service (throughput, response time, availability etc.).

Our solutions are mainly based on virtualized infrastructures that we apply from the IaaS to the SaaS levels. We are mainly concerned by the management and the execution of the applications by harnessing virtualization capabilities, the investigation of alternative solutions that aim at optimizing the trade-off between performance and energy costs of both applications and cloud resources, as well as arbitration policies in the cloud in the presence of energy-constrained resources.

ATLANMOD Project-Team

3. Research Program

3.1. MDE Foundations

Traditionally, models were often used as initial design sketches mainly aimed for communicating ideas among developers. On the contrary, MDE promotes models as the primary artifacts that drive all software engineering activities (i.e. not only software development but also evolution, reverse engineering, interoperability and so on) and are considered as the unifying concept [41]. Therefore, rigorous techniques for model definition and manipulation are the basis of any MDE framework.

The MDE community distinguishes three levels of models: (terminal) model, metamodel, and metametamodel. A terminal model is a (partial) representation of a system/domain that captures some of its characteristics (different models can provide different knowledge views on the domain and be combined later on to provide a global view). In MDE we are interested in terminal models expressed in precise modeling languages. The abstract syntax of a language, when expressed itself as a model, is called a metamodel. A complete language definition is given by an abstract syntax (a metamodel), one or more concrete syntaxes (the graphical or textual syntaxes that designers use to express models in that language) plus one or more definition of its semantics. The relation between a model expressed in a language and the metamodel of that language is called *conformsTo*. Metamodels are in turn expressed in a modeling language called metamodeling language. Similar to the model/metamodel relationship, the abstract syntax of a metamodeling language is called a metametamodel and metamodels defined using a given metamodeling language must conform to its metametamodel. Terminal models, metamodels, and metametamodel form a three-level architecture with levels respectively named M1, M2, and M3. A formal definition of these concepts is provided in [49] and [42]. MDE promotes *unification by models*, like object technology proposed in the eighties *unification by objects* [39]. These MDE principles may be implemented in several standards. For example, OMG proposes a standard metametamodel called Meta Object Facility (MOF) while the most popular example of metamodel in the context of OMG standards is the UML metamodel.

In our view the main way to automate MDE is by providing model manipulation facilities in the form of model transformation operations that taking one or more models as input generate one or more models as output (where input and output models are not necessarily conforming to the same metamodel). More specifically, a model transformation Mt defines the production of a model Mb from a model Ma. When the source and target metamodels (MMs) are identical ($MMa = MMb$), we say that the transformation is endogenous. When this is not the case ($MMa \neq MMb$) we say the transformation is exogenous. An example of an endogenous transformation is a UML refactoring that transforms public class attributes into private attributes while adding accessor methods for each transformed attribute. Many other operations may be considered as transformations as well. For example verifications or measurements on a model can be expressed as transformations [44]. One can see then why large libraries of reusable modeling artifacts (mainly metamodels and transformations) will be needed.

Another important idea is the fact that a model transformation is itself a model [40]. This means that the transformation program Mt can be expressed as a model and as such conforms to a metamodel MMt. This allows an homogeneous treatment of all kinds of terminal models, including transformations. Mt can be manipulated using the same existing MDE techniques already developed for other kinds of models. For instance, it is possible to apply a model transformation Mt' to manipulate Mt models. In that case, we say that Mt' is a higher order transformation (HOT), i.e. a transformation taking other transformations (expressed as transformation models) as input or/and producing other transformations as output.

As MDE developed, it became apparent that this was a branch of language engineering [43]. In particular, MDE offers an improved way to develop DSLs (Domain-Specific Languages). DSLs are programming or modeling languages that are tailored to solve specific kinds of problems in contrast with General Purpose Languages (GPLs) that aim to handle any kind of problem. Java is an example of a programming GPL and UML an example of a modeling GPL. DSLs are already widely used for certain kinds of programming; probably the best-known example is SQL, a language specifically designed for the manipulation of relational data in databases. The main benefit of DSLs is that they allow everybody to write programs/models using the concepts that actually make sense to their domain or to the problem they are trying to solve (for instance Matlab has matrices and lets the user express operations on them, Excel has cells, relations between cells, and formulas and allows the expression of simple computations in a visual declarative style, etc.). As well as making domain code programmers more productive, DSLs also tend to offer greater optimization opportunities. Programs written with these DSLs may be independent of the specific hardware they will eventually run on. Similar benefits are obtained when using modeling DSLs. In MDE, new DSLs can be easily specified by using the metamodel concept to define their abstract syntax. Models specified with those DSLs can then be manipulated by means of model transformations (with ATL for example [48]).

When following the previously described principles, one may take advantage of the uniformity of the MDE organization. As an example, considering similarly models of the static architecture and models of the dynamic behavior of a system allows at the same time economy of concepts and economy of implementation.

The following sections describe the main MDE research challenges the team is addressing. They go beyond the development of core MDE techniques (topic on which the team, as mentioned above, has largely contributed in the past, and that we believe is quite well-covered already) and focus on new aspects that are critical for the successful application of MDE in industrial contexts.

3.2. Reverse Engineering

One important domain that is being investigated by the AtlanMod team is the reverse engineering of existing IT systems. We do believe that efficiently dealing with such legacy systems is one of the main challenges in Software Engineering and related industry today. Having a better understanding of these systems in order to document, maintain, improve or migrate them is thus a key requirement for both academic and industrial actors in this area. However, it is not an easy task and it still raises interesting challenging issues to be explored [46].

We have shown how reverse engineering practices may be advantageously revisited with the help of the MDE approach and techniques, applying (as base principle) the systematic representation as models of the required information discovered from the legacy software artifacts (e.g. source code, configuration files, documentation, metadata, etc). The rise in abstraction allowed by MDE can bring new hopes that reverse engineering is now able to move beyond more traditional ad-hoc practices. For instance, a industrial PhD in partnership with IBM France aimed to investigate the possibilities of conceptualizing a generic framework enabling the extraction of business rules from a legacy application, as much as possible, independently of the language used to code it. Moreover, different pragmatic solutions for improving the overall scalability when dealing with large-scale legacy systems (handling huge data volumes) are intensively studied by the team.

In this context, AtlandMod has set up within the past years and is still developing the open source Eclipse MoDisco project (see 5.2). MoDisco is notably being referenced by the OMG ADM (Architecture Driven Modernization) normalization task force as the reference implementation for several of its standard metamodels. It is also used practically and improved in various collaborative projects the team is currently involved in (e.g. FP7 ARTIST). Complementary to the work based on MoDisco, we have also been experimenting (still in an industrial context, cf. TEAP FUI project) on the related problem of data federation from heterogeneous sources in the domain of Enterprise Architecture. This has notably resulted in a prototype called EMF Views that can be practically used in such reverse engineering scenarios.

Reverse engineering techniques have also been used in the context of the Web. In the last years the development of Web APIs has become a discipline that companies have to master to succeed in the Web. The so-called API

economy requires, on the one hand, companies to provide access to their data by means of Web APIs and, on the other hand, web developers to study and integrate such APIs into their applications. The exchange of data with these APIs is usually performed by using JSON, a schemaless data format easy for computers to parse and use. While JSON data is easy to read, its structure is implicit, thus entailing serious problems when integrating APIs coming from different vendors. Web developers have therefore to understand the domain behind each API and study how they can be composed. We tackle this problem by developing a MDE-based process able to reverse engineer the domain of Web APIs and to identify composition links among them. The approach therefore allows developers to easily visualize what is behind the API and the connections points that may be used in their applications.

We have recently opened a new research line in the context software analysis, in particular, in the Open-Source Software (OSS) field. The development of OSS follows a collaborative model where any developer can contribute to the advance of the project. To enable this collaboration, OSS projects use a plethora of tools such as forums, issue-trackers and Q&A websites, that developers can adopt to coordinate each other in the development process. Such a collaboration environment includes adapted solutions and provides effective communication means, but also causes scattering of the collaboration data, which hamper the understanding of the whole development process (e.g., who is leading the development or making the decisions). In this context, we propose to use reverse engineering techniques to better understand how OSS projects are developed in a broad sense, thus taking into account the different collaboration tools used and how they influence in the development of OSS projects.

3.3. Security Engineering

Several components are required to build up a system security architecture, such as firewalls, database user access control, intrusion detection systems, and VPN (Virtual Private Network) routers. These components must be properly configured to provide an appropriate degree of security to the system. The configuration process is highly complex and error-prone. In most organizations, security components are either manually configured based on security administrators expertise and flair; or simply recycled from existing configurations already deployed in other systems (even if they may not be appropriated for the current one). These practices put at risk the security of the whole organization.

As a first step we intend to apply model-driven techniques for the extraction of high level model representations of security policies enforced by system components like networks of firewalls, RDBMS and CMSs. Firewalls, core components in network security systems, are generally configured by using very low level vendor specific rule-based languages, difficult to understand and to maintain. As a consequence, as the configuration files grow, understanding which security policy is being actually enforced or checking if inconsistencies has been introduced becomes a very complex and time consuming task. Similarly, in RDBMSs and CMSs policies are configured and stored by using different, often low-level, mechanisms.

We propose to raise the level of abstraction so that the user can deal directly with the high level policies. Once a model representation of the enforced policy is available, model-driven techniques will ease some of the tasks we need to perform, like consistency checking, validation, querying and visualization. Easy migration between different vendors will be also enabled.

As a further step we intend to apply model-driven techniques for the integration of the diverse security policies extracted from concrete system components. In the case of complex systems composed of a number of interacting heterogeneous subsystems, access-control is pervasive with respect to their architecture. As mentioned above, we can find access-control enforcement rules in different components placed at different architectural levels where rules in a component may impact the execution of the security rules of another component. In addition, the access-control techniques implemented in each component may follow different AC models in order to best suit the needs of the component. Thus, ideally, a global representation of the access-control policy of the whole system should be available, as analysing a component policy in isolation does not provide enough information. Unfortunately, most times this global policy is not explicit or is outdated. This step requires to unveil the implicit dependencies between the set of policies working in an encompassing

system, so that a model representing the global AC policy can be built and the global analysis of the AC security is enabled

3.4. Software Quality

As with any type of production, an essential part of software production is determining the quality of the software. The level of quality associated to a software product is inevitably tied to properties such as how well it was developed and how useful it is to its users. AtlanMod team focus on researching techniques for the formal verification and testing of software models and model transformations.

These techniques must be applied at the model level (to evaluate the quality of specific software designs) and at the metamodel level (to evaluate the quality of modeling languages). In both cases, the Object Constraint Language (OCL) of the OMG is widely accepted as a standard textual language to complement (meta)model specifications with all those rules/constraints that cannot be easily defined using graphical modeling constructs.

Among all possible properties to verify, we take as the basic property the *satisfiability* property, from which many others may be derived (as liveliness, redundancy, subsumption,...). Satisfiability checks whether it is possible to create a valid instantiation (i.e. one that respects all modeling constraints) of a give (meta)model. Satisfiability is an undedicable problem when general OCL constraints are used as part of the model definition.

To deal with this problem, the team maintains the tool EMFtoCSP which translates the model verification challenge into the domain of constraint logic programming (CLP) for which sophisticated decision procedures exist. The tool integrates the described functionality in the Eclipse Modeling Framework (EMF) and the Eclipse Modeling Tools (MDT), making the functionality available for MDE in practice.

To complement these formal verification techniques we are also working on testing techniques, specially to optimize the testing of model transformations. White-box testing for model transformations is a technique that involves the extraction of knowledge embedded in the transformation code to generate test models. In our work, we apply static analysis techniques to model transformation specifications and represent the extracted knowledge as partial models that can drive the generation of highly effective test models (specially in terms of coverage).

3.5. Collaborative Development

Software development processes are collaborative in nature. The active participation of end-users in the early phases of the software development life-cycle is key when developing software. Among other benefits, the collaboration promotes a continual validation of the software to be build, thus guaranteeing that the final software will satisfy the users' needs. In this context, we have opened two novel research lines focused on the collaborative development *in* MDE and the collaborative development *with* MDE. The former is aimed at promoting the collaboration in the context of MDE while the latter uses MDE techniques to promote the participation in software development processes.

Collaboration is important in the context of MDE, in particular, when creating Domain-Specific Modeling Languages (DSMLs) which are (modeling) languages specifically designed to carry out the tasks of a particular domain. While end-users are actually the experts of the domain for which a DSML is developed, their participation in the DSML specification process is still rather limited nowadays (they are normally only involved in providing domain knowledge or testing the resulting language). This means that the MDE technical experts and not end-users are the ones in control of the DSML construction and evolution. This is a problem because errors in understanding the domain may hamper the development process and the quality of the resulting DSML. Thus, it would be beneficial to promote a more active participation of end-users in the DSML development process.

We have been working on the required support to make effective this participation, in particular, we have developed Collaboro, an approach which enables the involvement of the community (i.e., end-users and developers) in the DSML creation process. Collaboro allows modeling the collaborations between community members taking place during the definition of a new DSML and supports both the collaborative definition of

the abstract (i.e., metamodel) and concrete (i.e., notation) syntaxes for DSMLs by providing specific constructs to enable the discussion. Thus, each community member will have the chance to request changes, propose solutions and give an opinion (and vote) about those from others. We believe this discussion will enrich the language definition significantly and ensure that the end result satisfies as much as possible the expectations of the end-users. Collaboro has also been extended to support the example-driven development of DSMLs, thus promoting the engagement of end-users in the process.

The lessons learnt from this MDE-focused collaboration research are now being applied to the more general context of software development. In particular, our interest is to study how software development processes are governed (i.e. how the collaboration among developers and user takes place). Any software development project has to cope with a huge number of tasks consisting of either implementing new issues or fixing bugs. Thus, effective and precise prioritization of these tasks is key for the success of the project. Governance rules enable the coordination of developers in order to advance the project. Despite their importance, in practice governance rules are hardly ever explicitly defined, specially in the context of Open Source Systems (OSS), where it is hard to find a explicit system-level design, a project plan, schedule or list of deliverables. To alleviate this situation, mechanisms to facilitate the communication and the assignment of work are considered crucial for the success of the development. Tracking and issue-tracking systems, mailing lists and forums are broadly used to manage the tasks to be performed. While these tools provide a convenient compartmentalization of work and effective means of communication, they fall short in providing adequate support for specifying and enforcing governance rules (e.g. supporting the voting of tasks, easy tracking of decisions made in the project, etc.).

Thus, we believe the explicit definition of governance rules along with the corresponding infrastructure to help developers follow them would have several benefits, including improvements in the transparency of the decision-making process, traceability (being able to track why a decision was made and who decided it) and the automation of the governance process (e.g. liberating developers from having to be aware and follow the rules manually, minimizing the risk of inconsistent behaviour in the evolution of the project). We resort on MDE techniques to tackle this problem and provide a DSL specially adapted to the domain of governance in software projects to let project managers easily define the governance rules of their projects.

3.6. Scalability

As MDE is increasingly applied to larger and more complex industrial applications, the current generation of modelling and model management technologies are being stressed to their limits in terms of their capacity to accommodate collaborative development, efficient management and persistence of models larger than a few hundreds of megabytes in size. Additional research and development is imperative in order to enable MDE to remain relevant with industrial practice and to continue delivering its widely recognised productivity, quality, and maintainability benefits. Achieving scalability in modelling and MDE involves being able to construct large models and domain-specific languages in a systematic manner, enabling teams of modellers to construct and refine large models in a collaborative manner, advancing the state-of-the-art in model querying and transformations tools so that they can cope with large models (of the scale of millions of model elements), and providing an infrastructure for efficient storage, indexing and retrieval of large models. AtlanMod wants to provide a solution for these aspects of scalability in MDE by extending the Eclipse modeling framework, to create an open-source solution to scalable modeling in industry.

3.7. Industrialization of open source tools

Research labs, as a source of innovation, are potential key actors of the Software Engineering market. However, an important collaborative effort with the other players in the software industry is still needed in order to actually transfer the corresponding techniques or technologies from the research lab to a company. Based on the AtlanMod concrete experience with the previously mentioned open source tools/projects, we have extracted a pragmatic approach [4] for transforming the results of scientific experimentation into practical industrial solutions.

While dealing with innovation, this approach is also innovation-driven itself, as the action is actually conducted by the research lab via a technology transfer. Three different partners are directly involved in this process, using open source as the medium for maintaining a constant interaction between all of them:

- **Use Case Provider.** Usually a company big enough to have to face real complex industrial scenarios which need to be solved (at least partially) by applying new innovative principles and techniques;
- **Research Lab.** Usually a group from a research institute (public or private) or university evaluating the scientific relevance of the problems, identifying the research challenges and prototyping possible solutions;
- **Technology Provider.** Usually a small or medium company, with a particular technical expertise on the given domain or Software Engineering field, building and delivering the industrial version of the designed solutions;

From our past and current experience, three main characteristics of this industrialization *business model* can be highlighted:

- **Win-win situation.** Each partner can actually focus on its core activity while also directly benefiting from the results obtained by the others (notably the research lab can continue to do research);
- **Application-driven context.** The end-user need is at the origin of the process, which finally makes the developed solution actually relevant;
- **Iterative process.** The fact of having three distinct partners requires different regular and consecutive exchanges between all of them.

CIDRE Project-Team

3. Research Program

3.1. Our perspective

For many aspects of our everyday life, we rely heavily on information systems, many of which are based on massively networked devices that support a population of interacting and cooperating entities. While these information systems become increasingly open and complex, accidental and intentional failures get considerably more frequent and severe.

Two research communities traditionally address the concern of accidental and intentional failures: the distributed computing community and the security community. While both these communities are interested in the construction of systems that are correct and secure, an ideological gap and a lack of communication exist between them that is often explained by the incompatibility of the assumptions each of them traditionally makes. Furthermore, in terms of objectives, the distributed computing community has favored systems availability while the security community has focused on integrity and confidentiality, and more recently on privacy.

By contrast with this traditional conception, we are convinced that by looking at information systems as a combination of possibly revisited basic protocols, each one specified by a set of properties such as synchronization and agreement, security properties should emerge. This vision is shared by others and in particular by Myers *et al.* [63], whose objectives are to explore new methods for constructing distributed systems that are trustworthy in the aggregate even when some nodes in the system have been compromised by malicious attackers.

In accordance with this vision, the first main characteristic of the CIDRE group is to gather researchers from the two aforementioned communities, in order to address intentional failures, using foundations and approaches coming from both communities.

The second main characteristic of the CIDRE group lies in the scope of the systems it considers. Indeed, we consider three complementary levels of study:

- The Node Level: The term node either refers to a device that hosts a network client or service or to the process that runs this client or service. Node security management must be the focus of a particular attention, since from the user point of view, security of his own devices is crucial. Sensitive information and services must therefore be locally protected against various forms of attacks. This protection may take a dual form, namely prevention and detection.
- The Group Level: Distributed applications often rely on the identification of sets of interacting entities. These subsets are either called groups, clusters, collections, neighborhoods, spheres, or communities according to the criteria that define the membership. Among others, the adopted criteria may reflect the fact that its members are administrated by a unique person, or that they share the same security policy. It can also be related to the localization of the physical entities, or the fact that they need to be strongly synchronized, or even that they share mutual interests. Due to the vast number of possible contexts and terminologies, we refer to a single type of set of entities, that we call set of nodes. We assume that a node can locally and independently identify a set of nodes and modify the composition of this set at any time. The node that manages one set has to know the identity of each of its members and should be able to communicate directly with them without relying on a third party. Despite these two restrictions, this definition remains general enough to include as particular cases most of the examples mentioned above. Of course, more restrictive behaviors can be specified by adding other constraints. We are convinced that security can benefit from the existence and the identification of sets of nodes of limited size as they can help in improving the efficiency of the detection and prevention mechanisms.

- The Open Network Level: In the context of large-scale distributed and dynamic systems, interaction with unknown entities becomes an unavoidable habit despite the induced risk. For instance, consider a mobile user that connects his laptop to a public Wifi access point to interact with his company. At this point, data (regardless if it is valuable or not) is updated and managed through non trusted undedicated entities (i.e., communication infrastructure and nodes) that provide multiple services to multiple parties during that user connection. In the same way, the same device (e.g., laptop, PDA, USB key) is often used for both professional and private activities, each activity accessing and manipulating decisive data.

The third characteristic of the CIDRE group is to focus on three different aspects of security, namely trust, intrusion detection, and privacy as well as on the bridges that exist between these aspects. Indeed, we believe that to study new security solutions for nodes, set of nodes and open network levels, one must take into account that it is now a necessity to interact with devices whose owners are unknown. To reduce the risk of relying on dishonest entities, a trust mechanism is an essential prevention tool that aims at measuring the capacity of a remote node to provide a service compliant with its specification. Such a mechanism should allow to overcome ill-founded suspicions and to be aware of established misbehaviors. To identify such misbehaviors, intrusion detection systems are necessary. Such systems aim at detecting, by analyzing data flows, whether violations of the security policies have occurred. Finally, Privacy, which is now recognized as a fundamental individual right, should be respected despite the presence of tools and systems that continuously observe or even control users actions or behaviors.

3.2. Intrusion Detection

By exploiting vulnerabilities in operating systems, applications, or network services, an attacker can defeat preventive security mechanisms and violate the security policy of the whole system. The goal of intrusion detection systems (IDS) is to detect, by analyzing some data generated on a monitored system, violations of the security policy. From our point of view, while useful in practice, misuse detection is intrinsically limited. Indeed, it requires to update the signatures database in real-time similarly to what has to be done for antivirus tools. Given that there are thousands of machines that are every day victims of malware, such an approach may appear as insufficient especially due to the incredible expansion of malware, drastically limiting the capabilities of human intervention and response. The CIDRE group takes the alternative approach, namely the anomaly approach, which consists in detecting a deviation from a referenced behavior. Specifically, we propose to study three complementary methods:

- Illegal Flow Detection: This first method intends to detect information flows that violate the security policy [66], [62]. Our goal is here to detect information flows in the monitored system that are allowed by the access control mechanism, but are illegal from the security policy point of view.
- Data Corruption Detection: This second method aims at detecting intrusions that target specific applications, and make them execute illegal actions by using these applications incorrectly [60], [65]. This approach complements the previous one in the sense that the incorrect use of the application can possibly be legal from the point of view of the information flows and access control mechanisms, but is incorrect considering the security policy.
- Visualization: This third method relies on the capacity of human beings in detecting patterns and outliers in datasets when these datasets are properly visually represented. Human beings also know pieces of contextual information that are very difficult to formalize so as to make them usable by a computer. Visualization is therefore a very useful complementary tool to detect abnormal events in real time (monitoring), to search for malicious events in log files (data exploration and forensics) and to communicate results (reporting).

In these approaches, the access control mechanisms or the monitored applications can be either configured and executed on a single node, or distributed on a set of nodes. Thus, our approach must be studied at least at these two levels.

Here are some concrete examples of our research objectives (both short term and long term objectives) in the intrusion detection field:

- At node level, we apply the defensive programming approach (coming from the dependability field) to data corruption detection. The challenge is to determine which invariant/properties must be and can be verified either at runtime or statically. Regarding illegal flow detection, we try to extend this method to build anti-viruses by determining viruses signatures.
- At the set of nodes level, we revisit the distributed problems such as clock synchronization, logical clocks, consensus, properties detection, to extend the solutions proposed at node levels to cope with distributed flow control checking mechanisms. Regarding illegal flow detection, we study the collaboration and consistency at the node and set of nodes levels to obtain a global intrusion detection mechanism. Regarding the data corruption detection approach, our challenge is to identify local predicates/properties/invariants so that global predicates/properties/invariants would emerge at the system level.

3.3. Privacy

In our world of ubiquitous technologies, each individual constantly leaves digital traces related to his activities and interests which can be linked to his identity. The protection of privacy is one of the greatest challenge that lies ahead and also an important condition for the development of the Information Society. Moreover, due to legality and confidentiality issues, issues linked to privacy emerge naturally for applications working on sensitive data, such as medical records of patients or proprietary datasets of enterprises. Privacy Enhancing Technologies (PETs) are generally designed to respect both the principles of data minimization and data sovereignty. The data minimization principle states that only the information necessary to complete a particular application should be disclosed (and no more). This principle is a direct application of the legitimacy criteria defined by the European data protection directive (Article 7). This directive is currently being revised into a regulation that is going to strengthen the privacy rights of individuals and puts forward the concept of "privacy-by-design", which integrates the privacy aspects into the conception phase of a service or product. The data sovereignty principle states that data related to an individual belong to him and that he should stay in control of how this data is used and for which purpose. This principle can be seen as an extension of many national legislations on medical data that consider that a patient record belongs to the patient, and not to the doctors that create or update it, nor to the hospital that stores it. A fundamental hindrance to the achievement of sovereignty is that the trust assumptions given to external entities are often too optimistic, and thus they are many realistic situations in which they might betrayed.

In the CIDRE project, we investigate PETs operating at three different levels (node, set of nodes or open distributed system) and that are generally based on a mix of different foundations such as cryptographic techniques, security policies and access control mechanisms just to name a few. Examples of domains in which privacy and utility aspects collide and that are studied within the context of CIDRE include: identity management, location-based services, social networks, distributed systems and data mining. Here are some concrete examples of our research goals in the privacy field:

- at the node level, we design privacy-preserving identification scheme, automated reasoning on privacy policies [64], and policy-based adaptive PETs.
- at the set of nodes level, we augment distributed algorithms with privacy properties such as anonymity, unlinkability and unobservability.
- at the open distributed system level, we target both privacy concerns linked to disclosure of location (that typically occur in location-based services) and privacy issues in social networks. In the former case, we adopt a sanitization approach while in the latter one we consider privacy policies at user level, and their enforcement by all the intervening actors (e.g, at the level of the social network providers, of intermediate servers or of individual peers). We design novel algorithms for the resolution of privacy policy conflicts between autonomous entities, taking new concepts into consideration, such as the notion of equity in the context of an access control decision.

3.4. Trust Management

While the distributed computing community relies on the trustworthiness of its algorithms to ensure systems availability, the security community historically makes the hypothesis of a Trusted Computing Base (TCB) that contains the security mechanisms (such as access controls, and cryptography) implementing the security policy. Unfortunately, as information systems get increasingly complex and open, the TCB management may itself get very complex, dynamic and error-prone. From our point of view, an appealing approach is to distribute and manage the TCB on each node and to leverage the trustworthiness of the distributed algorithms to strengthen each node's TCB. Accordingly, the CIDRE group studies automated trust management systems at all the three identified levels:

- at the node level, such a system should allow each node to evaluate by itself the trustworthiness of its neighborhood and to self-configure the security mechanisms it implements;
- at the group level, such a system might rely on existing trust relations with other nodes of the group to enhance the significance and the reliability of the gathered information;
- at the open network level, such a system should rely on reputation mechanisms to estimate the trustworthiness of the peers the node interacts with. The system might also benefit from the information provided by *a priori* trusted peers that, for instance, would belong to the same group (see previous item).

For the last two items, the automated trust management system will de facto follow the distributed computing approach. As such, emphasis will be put on the trustworthiness of the designed distributed algorithms. Thus, the proposed approach will provide both the adequate security mechanisms and a trustworthy distributed way of managing them. Regarding trust management, we still have research goals that are to be tackled. We briefly list hereafter some of our short and long term objectives at node, group and open networks levels:

1. At node level, we investigate how implicit trust relationships identified and deduced by a node during its interactions with its neighborhood could be explicitly used by the node (for instance by means of a series of rules) to locally evaluate the trustworthiness of its neighborhood. The impact of trust on the local security policy, and on its enforcement will be studied accordingly.
2. At the set of nodes level, we take advantage of the pre-existing trust relationship among the set of nodes to design composition mechanisms that would guarantee that automatically configured security policies are consistent with each group member security policy.
3. At the open distributed system level, we design reputation mechanisms to both defend the system against specific attacks (whitewashing, bad mouthing, ballot stuffing, isolation) by relying on the properties guaranteed at nodes and set of nodes levels, and guaranteeing persistent and safe feedback, and for specific cases in guaranteeing the right to be forgotten (i.e., the right to data erasure).

DIONYSOS Project-Team

3. Research Program

3.1. Introduction

The scientific foundations of our work are those of network design and network analysis. Specifically, this concerns the principles of packet switching and in particular of IP networks (protocol design, protocol testing, routing, scheduling techniques), and the mathematical and algorithmic aspects of the associated problems, on which our methods and tools are based.

These foundations are described in the following paragraphs. We begin by a subsection dedicated to Quality of Service (QoS) and Quality of Experience (QoE), since they can be seen as unifying concepts in our activities. Then we briefly describe the specific sub-area of model evaluation and about the particular multidisciplinary domain of network economics.

3.2. Quality of Service and Quality of Experience

Since it is difficult to develop as many communication solutions as possible applications, the scientific and technological communities aim towards providing general *services* allowing to give to each application or user a set of properties nowadays called "Quality of Service" (QoS), a terminology lacking a precise definition. This QoS concept takes different forms according to the type of communication service and the aspects which matter for a given application: for performance it comes through specific metrics (delays, jitter, throughput, etc.), for dependability it also comes through appropriate metrics: reliability, availability, or vulnerability, in the case for instance of WAN (Wide Area Network) topologies, etc.

QoS is at the heart of our research activities: We look for methods to obtain specific "levels" of QoS and for techniques to evaluate the associated metrics. Our ultimate goal is to provide tools (mathematical tools and/or algorithms, under appropriate software "containers" or not) allowing users and/or applications to attain specific levels of QoS, or to improve the provided QoS, if we think of a particular system, with an optimal use of the resources available. Obtaining a good QoS level is a very general objective. It leads to many different areas, depending on the systems, applications and specific goals being considered. Our team works on several of these areas. We also investigate the impact of network QoS on multimedia payloads to reduce the impact of congestion.

Some important aspects of the behavior of modern communication systems have subjective components: the quality of a video stream or an audio signal, *as perceived by the user*, is related to some of the previous mentioned parameters (packet loss, delays, ...) but in an extremely complex way. We are interested in analyzing these types of flows from this user-oriented point of view. We focus on the *user perceived quality*, the main component of what is nowadays called Quality of Experience (in short, QoE), to underline the fact that, in this case, we want to center the analysis on the user. In this context, we have a global project called PSQA, which stands for Pseudo-Subjective Quality Assessment, and which refers to a methodology allowing to automatically measure QoE.

Another special case to which we devote research efforts in the team is the analysis of qualitative properties related to interoperability assessment. This refers to the act of determining if end-to-end functionality between at least two communicating systems is as required by the base standards for those systems. Conformance is the act of determining to what extent a single component conforms to the individual requirements of the standard it is based on. Our purpose is to provide such a formal framework (methods, algorithms and tools) for interoperability assessment, in order to help in obtaining efficient interoperability test suites for new generation networks, mainly around IPv6-related protocols. The interoperability test suites generation is based on specifications (standards and/or RFCs) of network components and protocols to be tested.

3.3. Stochastic modeling

The scientific foundations of our modeling activities are composed of stochastic processes theory and, in particular, Markov processes, queuing theory, stochastic graphs theory, etc. The objectives are either to develop numerical solutions, or analytical ones, or possibly discrete event simulation or Monte Carlo (and Quasi-Monte Carlo) techniques. We are always interested in model evaluation techniques for dependability and performability analysis, both in static (network reliability) and dynamic contexts (depending on the fact that time plays an explicit role in the analysis or not). We look at systems from the classical so-called *call level*, leading to standard models (for instance, queues or networks of queues) and also at the *burst level*, leading to *fluid models*.

In recent years, our work on the design of the topologies of WANs led us to optimization techniques, in particular in the case of very large optimization problems, usually formulated in terms of graphs. The associated methods we are interested in are composed of simulated annealing, genetic algorithms, TABU search, etc. For the time being, we have obtained our best results with GRASP techniques.

Network pricing is a good example of a multi-disciplinary research activity half-way between applied mathematics, economy and networking, centered on stochastic modeling issues. Indeed, the Internet is facing a tremendous increase of its traffic volume. As a consequence, real users complain that large data transfers take too long, without any possibility to improve this by themselves (by paying more, for instance). A possible solution to cope with congestion is to increase the link capacities; however, many authors consider that this is not a viable solution as the network must respond to an increasing demand (and experience has shown that demand of bandwidth has always been ahead of supply), especially now that the Internet is becoming a commercial network. Furthermore, incentives for a fair utilization between customers are not included in the current Internet. For these reasons, it has been suggested that the current flat-rate fees, where customers pay a subscription and obtain an unlimited usage, should be replaced by usage-based fees. Besides, the future Internet will carry heterogeneous flows such as video, voice, email, web, file transfers and remote login among others. Each of these applications requires a different level of QoS: for example, video needs very small delays and packet losses, voice requires small delays but can afford some packet losses, email can afford delay (within a given bound) while file transfer needs a good average throughput and remote login requires small round-trip times. Some pricing incentives should exist so that each user does not always choose the best QoS for her application and so that the final result is a fair utilization of the bandwidth. On the other hand, we need to be aware of the trade-off between engineering efficiency and economic efficiency; for example, traffic measurements can help in improving the management of the network but is a costly option. These are some of the various aspects often present in the pricing problems we address in our work. More recently, we have switched to the more general field of network economics, dealing with the economic behavior of users, service providers and content providers, as well as their relations.

DIVERSE Project-Team

3. Research Program

3.1. Scientific background

3.1.1. Model-driven engineering

Model-Driven Engineering (MDE) aims at reducing the accidental complexity associated with developing complex software-intensive systems (e.g., use of abstractions of the problem space rather than abstractions of the solution space) [148]. It provides DIVERSE with solid foundations to specify, analyze and reason about the different forms of diversity that occur through the development lifecycle. A primary source of accidental complexity is the wide gap between the concepts used by domain experts and the low-level abstractions provided by general-purpose programming languages [116]. MDE approaches address this problem through modeling techniques that support separation of concerns and automated generation of major system artifacts from models (*e.g.,* test cases, implementations, deployment and configuration scripts). In MDE, a model describes an aspect of a system and is typically created or derived for specific development purposes [94]. Separation of concerns is supported through the use of different modeling languages, each providing constructs based on abstractions that are specific to an aspect of a system. MDE technologies also provide support for manipulating models, for example, support for querying, slicing, transforming, merging, and analyzing (including executing) models. Modeling languages are thus at the core of MDE, which participates to the development of a sound *Software Language Engineering*[0], including an unified typing theory that integrate models as first class entities [151].

Incorporating domain-specific concepts and high-quality development experience into MDE technologies can significantly improve developer productivity and system quality. Since the late nineties, this realization has led to work on MDE language workbenches that support the development of domain-specific modeling languages (DSMLs) and associated tools (*e.g.,* model editors and code generators). A DSML provides a bridge between the field in which domain experts work and the implementation (programming) field. Domains in which DSMLs have been developed and used include, among others, automotive, avionics, and the emerging cyber-physical systems. A study performed by Hutchinson et al. [123] provides some indications that DSMLs can pave the way for wider industrial adoption of MDE.

More recently, the emergence of new classes of systems that are complex and operate in heterogeneous and rapidly changing environments raises new challenges for the software engineering community. These systems must be adaptable, flexible, reconfigurable and, increasingly, self-managing. Such characteristics make systems more prone to failure when running and thus the development and study of appropriate mechanisms for continuous design and run-time validation and monitoring are needed. In the MDE community, research is focused primarily on using models at design, implementation, and deployment stages of development. This work has been highly productive, with several techniques now entering a commercialization phase. As software systems are becoming more and more dynamic, the use of model-driven techniques for validating and monitoring run-time behavior is extremely promising [131].

3.1.2. Variability modeling

While the basic vision underlying *Software Product Lines* (SPL) can probably be traced back to David Parnas seminal article [141] on the Design and Development of Program Families, it is only quite recently that SPLs are emerging as a paradigm shift towards modeling and developing software system families rather than individual systems [139]. SPL engineering embraces the ideas of mass customization and software reuse. It focuses on the means of efficiently producing and maintaining multiple related software products, exploiting what they have in common and managing what varies among them.

[0] See http://planet-sl.org

Several definitions of the *software product line* concept can be found in the research literature. Clements *et al.* define it as *a set of software-intensive systems sharing a common, managed set of features that satisfy the specific needs of a particular market segment or mission and are developed from a common set of core assets in a prescribed way* [138]. Bosch provides a different definition [103]: *A SPL consists of a product line architecture and a set of reusable components designed for incorporation into the product line architecture. In addition, the PL consists of the software products developed using the mentioned reusable assets*. In spite of the similarities, these definitions provide different perspectives of the concept: *market-driven*, as seen by Clements *et al.*, and *technology-oriented* for Bosch.

SPL engineering is a process focusing on capturing the *commonalities* (assumptions true for each family member) and *variability* (assumptions about how individual family members differ) between several software products [110]. Instead of describing a single software system, a SPL model describes a set of products in the same domain. This is accomplished by distinguishing between elements common to all SPL members, and those that may vary from one product to another. Reuse of core assets, which form the basis of the product line, is key to productivity and quality gains. These core assets extend beyond simple code reuse and may include the architecture, software components, domain models, requirements statements, documentation, test plans or test cases.

The SPL engineering process consists of two major steps:

1. **Domain Engineering**, or *development for reuse*, focuses on core assets development.
2. **Application Engineering**, or *development with reuse*, addresses the development of the final products using core assets and following customer requirements.

Central to both processes is the management of **variability** across the product line [118]. In common language use, the term *variability* refers to *the ability or the tendency to change*. Variability management is thus seen as the key feature that distinguishes SPL engineering from other software development approaches [104]. Variability management is thus growingly seen as the cornerstone of SPL development, covering the entire development life cycle, from requirements elicitation [153] to product derivation [158] to product testing [137], [136].

Halmans *et al.* [118] distinguish between *essential* and *technical* variability, especially at requirements level. Essential variability corresponds to the customer's viewpoint, defining what to implement, while technical variability relates to product family engineering, defining how to implement it. A classification based on the dimensions of variability is proposed by Pohl *et al.* [143]: beyond **variability in time** (existence of different versions of an artifact that are valid at different times) and **variability in space** (existence of an artifact in different shapes at the same time) Pohl *et al.* claim that variability is important to different stakeholders and thus has different levels of visibility: **external variability** is visible to the customers while **internal variability**, that of domain artifacts, is hidden from them. Other classification proposals come from Meekel *et al.* [129] (feature, hardware platform, performances and attributes variability) or Bass *et al.* [92] who discuss about variability at the architectural level.

Central to the modeling of variability is the notion of *feature*, originally defined by Kang *et al.* as: *a prominent or distinctive user-visible aspect, quality or characteristic of a software system or systems* [125]. Based on this notion of *feature*, they proposed to use a *feature model* to model the variability in a SPL. A feature model consists of a *feature diagram* and other associated information: *constraints* and *dependency rules*. Feature diagrams provide a *graphical tree-like notation depicting the hierarchical organization of high level product functionalities* represented as features. The root of the tree refers to the complete system and is progressively decomposed into more refined features (tree nodes). Relations between nodes (features) are materialized by *decomposition edges* and *textual constraints*. Variability can be expressed in several ways. Presence or absence of a feature from a product is modeled using *mandatory* or *optional features*. Features are graphically represented as rectangles while some graphical elements (e.g., unfilled circle) are used to describe the variability (e.g., a feature may be optional).

Features can be organized into *feature groups*. Boolean operators *exclusive alternative (XOR)*, *inclusive alternative (OR)* or *inclusive (AND)* are used to select one, several or all the features from a feature group.

Dependencies between features can be modeled using *textual constraints*: *requires* (presence of a feature requires the presence of another), *mutex* (presence of a feature automatically excludes another). Feature attributes can be also used for modeling quantitative (e.g., numerical) information. Constraints over attributes and features can be specified as well.

Modeling variability allows an organization to capture and select which version of which variant of any particular aspect is wanted in the system [104]. To implement it cheaply, quickly and safely, redoing by hand the tedious weaving of every aspect is not an option: some form of automation is needed to leverage the modeling of variability [96], [112]. Model Driven Engineering (MDE) makes it possible to automate this weaving process [124]. This requires that models are no longer informal, and that the weaving process is itself described as a program (which is as a matter of facts an executable meta-model [133]) manipulating these models to produce for instance a detailed design that can ultimately be transformed to code, or to test suites [142], or other software artifacts.

3.1.3. Component-based software development

Component-based software development [152] aims at providing reliable software architectures with a low cost of design. Components are now used routinely in many domains of software system designs: distributed systems, user interaction, product lines, embedded systems, etc. With respect to more traditional software artifacts (e.g., object oriented architectures), modern component models have the following distinctive features [111]: description of requirements on services required from the other components; indirect connections between components thanks to ports and connectors constructs [127]; hierarchical definition of components (assemblies of components can define new component types); connectors supporting various communication semantics [107]; quantitative properties on the services [101].

In recent years component-based architectures have evolved from static designs to dynamic, adaptive designs (e.g., SOFA [107], Palladio [97], Frascati [134]). Processes for building a system using a statically designed architecture are made of the following sequential lifecycle stages: requirements, modeling, implementation, packaging, deployment, system launch, system execution, system shutdown and system removal. If for any reason after design time architectural changes are needed after system launch (e.g., because requirements changed, or the implementation platform has evolved, etc) then the design process must be reexecuted from scratch (unless the changes are limited to parameter adjustment in the components deployed).

Dynamic designs allow for *on the fly* redesign of a component based system. A process for dynamic adaptation is able to reapply the design phases while the system is up and running, without stopping it (this is different from stop/redeploy/start). This kind of process supports *chosen adaptation*, when changes are planned and realized to maintain a good fit between the needs that the system must support and the way it supports them [126]. Dynamic component-based designs rely on a component meta-model that supports complex life cycles for components, connectors, service specification, etc. Advanced dynamic designs can also take platform changes into account at run-time, without human intervention, by adapting themselves [109], [155]. Platform changes and more generally environmental changes trigger *imposed adaptation*, when the system can no longer use its design to provide the services it must support. In order to support an eternal system [99], dynamic component based systems must separate architectural design and platform compatibility. This requires support for heterogeneity, since platform evolutions can be partial.

The Models@runtime paradigm denotes a model-driven approach aiming at taming the complexity of dynamic software systems. It basically pushes the idea of reflection one step further by considering the reflection layer as a real model "something simpler, safer or cheaper than reality to avoid the complexity, danger and irreversibility of reality [146]". In practice, component-based (and/or service-based) platforms offer reflection APIs that make it possible to introspect the system (which components and bindings are currently in place in the system) and dynamic adaptation (by applying CRUD operations on these components and bindings). While some of these platforms offer rollback mechanisms to recover after an erroneous adaptation, the idea of Models@runtime is to prevent the system from actually enacting an erroneous adaptation. In other words, the "model at run-time" is a reflection model that can be uncoupled (for reasoning, validation, simulation purposes) and automatically resynchronized.

Heterogeneity is a key challenge for modern component based system. Until recently, component based techniques were designed to address a specific domain, such as embedded software for command and control, or distributed Web based service oriented architectures. The emergence of the Internet of Things paradigm calls for a unified approach in component based design techniques. By implementing an efficient separation of concern between platform independent architecture management and platform dependent implementations, *Models@runtime* is now established as a key technique to support dynamic component based designs. It provides DIVERSE with an essential foundation to explore an adaptation envelop at run-time.

Search Based Software Engineering [120] has been applied to various software engineering problems in order to support software developers in their daily work. The goal is to automatically explore a set of alternatives and assess their relevance with respect to the considered problem. These techniques have been applied to craft software architecture exhibiting high quality of services properties [117]. Multi Objectives Search based techniques [114] deal with optimization problem containing several (possibly conflicting) dimensions to optimize. These techniques provide DIVERSE with the scientific foundations for reasoning and efficiently exploring an envelope of software configurations at run-time.

3.1.4. Validation and verification

Validation and verification (V&V) theories and techniques provide the means to assess the validity of a software system with respect to a specific correctness envelop. As such, they form an essential element of DIVERSE's scientific background. In particular, we focus on model-based V&V in order to leverage the different models that specify the envelop at different moments of the software development lifecycle.

Model-based testing consists in analyzing a formal model of a system (*e.g.*, activity diagrams, which capture high-level requirements about the system, statecharts, which capture the expected behavior of a software module, or a feature model, which describes all possible variants of the system) in order to generate test cases that will be executed against the system. Model-based testing [154] mainly relies on model analysis, constraint solving [113] and search-based reasoning [128]. DIVERSE leverages in particular the applications of model-based testing in the context of highly-configurable systems and [156] interactive systems [130] as well as recent advances based on diversity for test cases selection [121].

Nowadays, it is possible to simulate various kinds of models. Existing tools range from industrial tools such as Simulink, Rhapsody or Telelogic to academic approaches like Omega [140], or Xholon [0]. All these simulation environments operate on homogeneous environment models. However, to handle diversity in software systems, we also leverage recent advances in heterogeneous simulation. Ptolemy [106] proposes a common abstract syntax, which represents the description of the model structure. These elements can be decorated using different directors that reflect the application of a specific model of computation on the model element. Metropolis [93] provides modeling elements amenable to semantically equivalent mathematical models. Metropolis offers a precise semantics flexible enough to support different models of computation. ModHel'X [119] studies the composition of multi-paradigm models relying on different models of computation.

Model-based testing and simulation are complemented by runtime fault-tolerance through the automatic generation of software variants that can run in parallel, to tackle the open nature of software-intensive systems. The foundations in this case are the seminal work about N-version programming [91], recovery blocks [144] and code randomization [95], which demonstrated the central role of diversity in software to ensure runtime resilience of complex systems. Such techniques rely on truly diverse software solutions in order to provide systems with the ability to react to events, which could not be predicted at design time and checked through testing or simulation.

3.1.5. Empirical software engineering

The rigorous, scientific evaluation of DIVERSE's contributions is an essential aspect of our research methodology. In addition to theoretical validation through formal analysis or complexity estimation, we also aim at applying state-of-the-art methodologies and principles of empirical software engineering. This approach encompasses a set of techniques for the sound validation contributions in the field of software engineering,

[0] http://www.primordion.com/Xholon/

ranging from statistically sound comparisons of techniques and large-scale data analysis to interviews and systematic literature reviews [149], [147]. Such methods have been used for example to understand the impact of new software development paradigms [105]. Experimental design and statistical tests represent another major aspect of empirical software engineering. Addressing large-scale software engineering problems often requires the application of heuristics, and it is important to understand their effects through sound statistical analyses [90].

3.2. Research axis

Figure 1 illustrates the four dimensions of software diversity, which form the core research axis of DIVERSE: the **diversity of languages** used by the stakeholders involved in the construction of these systems; the **diversity of features** required by the different customers; the **diversity of runtime environments** in which software has to run and adapt; the **diversity of implementations** that are necessary for resilience through redundancy. These four axis share and leverage the scientific and technological results developed in the area of model-driven engineering in the last decade. This means that all our research activities are founded on sound abstractions to reason about specific aspects of software systems, compose different perspectives and automatically generate parts of the system.

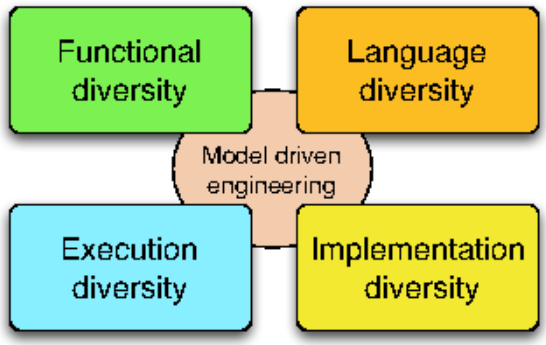


Figure 1. The four research axis of DIVERSE, which rely on a MDE scientific background

3.2.1. Software Language Engineering

The engineering of systems involves many different stakeholders, each with their own domain of expertise. Hence more and more organizations are adopting Domain Specific Modeling Languages (DSMLs) to allow domain experts to express solutions directly in terms of relevant domain concepts [148], [116]. This new trend raises new challenges about designing DSMLs, evolving a set of DSMLs and coordinating the use of multiple DSLs for both DSL designers and DSL users.

3.2.1.1. Challenges

Reusability of software artifacts is a central notion that has been thoroughly studied and used by both academics and industrials since the early days of software construction. Essentially, designing reusable artifacts allows the construction of large systems from smaller parts that have been separately developed and validated, thus reducing the development costs by capitalizing on previous engineering efforts. However, it is still hardly possible for language designers to design typical language artifacts (e.g. language constructs, grammars, editors or compilers) in a reusable way. The current state of the practice usually prevents the reusability of language artifacts from one language to another, consequently hindering the emergence of real engineering techniques around software languages. Conversely, concepts and mechanisms that enable artifacts reusability abound in the software engineering community.

Variability concerns in modeling languages occur in the definition of the abstract and concrete syntax as well as in the specification of the language's semantics. The major challenges met when addressing the need for variability are: (i) set principles for modeling language units that support the modular specification of a modeling language; and (ii) design mechanisms to assemble these units in a complete language, according to the set of authorized variation points for the modeling language family.

A new generation of complex software-intensive systems (for example smart health support, smart grid, building energy management, and intelligent transportation systems) presents new opportunities for leveraging modeling languages. The development of these systems requires expertise in diverse domains. Consequently, different types of stakeholders (e.g., scientists, engineers and end-users) must work in a coordinated manner on various aspects of the system across multiple development phases. DSMLs can be used to support the work of domain experts who focus on a specific system aspect, but they can also provide the means for coordinating work across teams specializing in different aspects and across development phases. The support and integration of DSMLs leads to what we call **the globalization of modeling languages**, *i.e.* the use of multiple languages for the coordinated development of diverse aspects of a system. One can make an analogy with world globalization in which relationships are established between sovereign countries to regulate interactions (e.g., travel and commerce related interactions) while preserving each country's independent existence.

3.2.1.2. Scientific objectives

We address reuse and variability challenges through the investigation of the time-honored concepts of substitutability, inheritance and components, evaluate their relevance for language designers and provide tools and methods for their inclusion in software language engineering. We will develop novel techniques for the modular construction of language extensions with the support of model syntactical variability. From the semantics perspective, we investigate extension mechanisms for the specification of variability in operational semantics, focusing on static introduction and heterogeneous models of computation. The definition of variation points for the three aspects of the language definition provides the foundations for the novel concept Language Unit (LU) as well as suitable mechanisms to compose such units.

We explore the necessary breakthrough in software languages to support modeling and simulation of heterogeneous and open systems. This work relies on the specification of executable domain specific modeling languages (DSMLs) to formalize the various concerns of a software-intensive system, and of models of computation (MoCs) to explicitly model the concurrency, time and communication of such DSMLs. We develop a framework that integrates the necessary foundations and facilities for designing and implementing executable and concurrent domain-specific modeling languages. It also provides unique features to specify composition operators between (possibly heterogeneous) DSMLs. Such specifications are amenable to support the edition, execution, graphical animation and analysis of heterogeneous models. The objective is to provide both a significant improvement of MoCs and DSMLs design and implementation; and the simulation based validation and verification of complex systems.

We see an opportunity for the automatic diversification of programs' computation semantics, for example through the diversification of compilers or virtual machines. The main impact of this artificial diversity is to provide flexible computation and thus ease adaptation to different execution conditions. A combination of static and dynamic analysis could support the identification of what we call *plastic computation zones* in the code. We identify different categories of such zones: (i) areas in the code in which the order of computation can vary (e.g., the order in which a block of sequential statements is executed); (ii) areas that can be removed, keeping the essential functionality [150] (e.g., skip some loop iterations); (iii) areas that can replaced by alternative code (e.g., replace a try-catch by a return statement). Once we know which zones in the code can be randomized, it is necessary to modify the model of computation to leverage the computation plasticity. This consists in introducing variation points in the interpreter to reflect the diversity of models of computation. Then, the choice of a given variation is performed randomly at run-time.

3.2.2. Variability Modeling and Engineering

The systematic modeling of variability in software systems has emerged as an effective approach to document and reason about software evolutions and heterogeneity (*cf.* Section 3.1.2). Variability modeling character-

izes an "envelope" of possible software variations. The industrial use of variability models and their relation to software artifact models require a complete engineering framework, including composition, decomposition, analysis, configuration and artifact derivation, refactoring, re-engineering, extraction, and testing. This framework can be used both to tame imposed diversity and to manage chosen diversity.

3.2.2.1. Challenges

A fundamental problem is that the **number of variants** can be exponential in the number of options (features). Already with 300 boolean configuration options, approximately 10^{90} configurations exist – more than estimated count of atoms in the universe. Domains like automotive or operating systems have to manage more than 10000 options (e.g., Linux). Practitioners face the challenge of developing billions of variants. It is easy to forget a necessary constraint, leading to the synthesis of unsafe variants, or to under-approximate the capabilities of the software platform. Scalable modelling techniques are therefore crucial to specify and reason about a very large set of variants.

Model-driven development supports two ways to deal with the increasing number of concerns in complex systems: (1) multi-view modeling, *i.e.* when modeling each concern separately, and variability modeling. However, there is little support to combine both approaches consistently. Techniques to integrate both approaches will enable the construction of a consistent set of views and variation points in each view.

The design, construction and maintenance of software families have a major impact on **software testing**. Among the existing challenges, we can cite: the selection of test cases for a specific variant; the evolution of test suites with integration of new variants; the combinatorial explosion of the number of software configurations to be tested. Novel model-based techniques for test generation and test management in a software product line context are needed to overcome state-of-the-art limits we already observed in some projects.

3.2.2.2. Scientific objectives

We aim at developing scalable techniques to automatically analyze variability models and their interactions with other views on the software intensive system (requirements, architecture, design). These techniques provide two major advancements in the state of the art: (1) an extension of the semantics of variability models in order to enable the definition of attributes (*e.g.*, cost, quality of service, effort) on features and to include these attributes in the reasoning; (2) an assessment of the consistent specification of variability models with respect to system views (since variability is orthogonal to system modeling, it is currently possible to specify the different models in ways that are semantically meaningless). The former aspect of analysis is tackled through constraint solving and finite-domain constraint programming, while the latter aspect is investigated through automatic search-based techniques (similar to genetic algorithms) for the exploration of the space of interaction between variability and view models.

We aim to develop procedures to reverse engineer dependencies and features' sets from existing software artefacts – be it source code, configuration files, spreadsheets (e.g., product comparison matrices) or requirements. We expect to scale up (e.g., for extracting a very large number of variation points) and guarantee some properties (e.g., soundness of configuration semantics, understandability of ontological semantics). For instance, when building complex software-intensive systems, textual requirements are captured in very large quantities of documents. In this context, adequate models to formalize the organization of requirements documents and automated techniques to support impact analysis (in case of changes in the requirements) have to be developed.

We aim at developing sound methods and tools to integrate variability management in model-based testing activities. In particular, we will leverage requirement models as an essential asset to establish formal relations between variation points and test models. These relations will form the basis for novel algorithms that drive the systematic selection of test configurations that satisfy well-defined test adequacy criteria as well as the generation of test cases for a specific product in the product line.

3.2.3. Heterogeneous and dynamic software architectures

Flexible yet dependable systems have to cope with heterogeneous hardware execution platforms ranging from smart sensors to huge computation infrastructures and data centers. Evolutions range from a mere change in the system configuration to a major architectural redesign, for instance to support addition of new features

or a change in the platform architecture (new hardware is made available, a running system switches to low bandwidth wireless communication, a computation node battery is running low, etc). In this context, we need to devise formalisms to reason about the impact of an evolution and about the transition from one configuration to another. It must be noted that this axis focuses on the use of models to drive the evolution from design time to run-time. Models will be used to (i) systematically define predictable configurations and variation points through which the system will evolve; (ii) develop behaviors necessary to handle unpredicted evolutions.

3.2.3.1. Challenges

The main challenge is to provide new homogeneous architectural modelling languages and efficient techniques that enable continuous software reconfiguration to react to changes. This work handles the challenges of handling the diversity of runtime infrastructures and managing the cooperation between different stakeholders. More specifically, the research developed in this axis targets the following dimensions of software diversity.

Platform architectural heterogeneity induces a first dimension of imposed diversity (type diversity). Platform reconfigurations driven by changing resources define another dimension of diversity (deployment diversity). To deal with these imposed diversity problems, we will rely on model based runtime support for adaptation, in the spirit of the dynamic distributed component framework developed by the Triskell team. Since the runtime environment composed of distributed, resource constrained hardware nodes cannot afford the overhead of traditional runtime adaptation techniques, we investigate the design of novel solutions relying on models@runtime and on specialized tiny virtual machines to offer resource provisioning and dynamic reconfigurations. In the next two years this research will be supported by the InfraJVM project.

Diversity can also be an asset to optimize software architecture. Architecture models must integrate multiple concerns in order to properly manage the deployment of software components over a physical platform. However, these concerns can contradict each other (*e.g.*, accuracy and energy). In this context, we investigate automatic solutions to explore the set of possible architecture models and to establish valid trade-offs between all concerns in case of changes.

3.2.3.2. Scientific objectives

Automatic synthesis of optimal software architectures. Implementing a service over a distributed platform (*e.g.*, a pervasive system or a cloud platform) consists in deploying multiple software components over distributed computation nodes. We aim at designing search-based solutions to (i) assist the software architect in establishing a good initial architecture (that balances between different factors such as cost of the nodes, latency, fault tolerance) and to automatically update the architecture when the environment or the system itself change. The choice of search-based techniques is motivated by the very large number of possible software deployment architectures that can be investigated and that all provide different trade-offs between qualitative factors. Another essential aspect that is supported by multi-objective search is to explore different architectural solutions that are not necessarily comparable. This is important when the qualitative factors are orthogonal to each other, such as security and usability for example.

Flexible software architecture for testing and data management. As the number of platforms on which software runs increases and different software versions coexist, the demand for testing environments also increases. For example, to test a software patch or upgrade, the number of testing environments is the product of the number of running environments the software supports and the number of coexisting versions of the software. Based on our first experiment on the synthesis of cloud environment using architectural models, our objective is to define a set of domain specific languages to catch the requirement and to design cloud environments for testing and data management of future internet systems from data centers to things. These languages will be interpreted to support dynamic synthesis and reconfiguration of a testing environment.

Runtime support for heterogeneous environments. Execution environments must provide a way to account or reserve resources for applications. However, current execution environments such as the Java Virtual Machine do not clearly define a notion of application: each framework has its own definition. For example, in OSGi, an application is a component, in JEE, an application is most of the time associated to a class loader, in the Multi-Tasking Virtual machine, an application is a process. The challenge consists in defining an execution environment that provides direct control over resources (CPU, Memory, Network I/O) independently from the

definition of an application. We propose to define abstract resource containers to account and reserve resources on a distributed network of heterogeneous devices.

3.2.4. Diverse implementations for resilience

Open software-intensive systems have to evolve over their lifetime in response to changes in their environment. Yet, most verification techniques assume a closed environment or the ability to predict all changes. Dynamic changes and evolutions thus represent a major challenge for these techniques that aim at assessing the correctness and robustness of the system. On the one hand, DIVERSE will adapt V&V techniques to handle diversity imposed by the requirements and the execution environment, on the other hand we leverage diversity to increase the robustness of software in face of unpredicted situations. More specifically, we address the following V&V challenges.

3.2.4.1. Challenges

One major challenge to build flexible and open yet dependable systems is that current software engineering techniques require architects to foresee all possible situations the system will have to face. However, openness and flexibility also mean unpredictability: unpredictable bugs, attacks, environmental evolutions, etc. Current fault-tolerance [144] and security [115] techniques provide software systems with the capacity of detecting accidental and deliberate faults. However, existing solutions assume that the set of bugs or vulnerabilities in a system does not evolve. This assumption does not hold for open systems, thus it is essential to revisit fault-tolerance and security solutions to account for diverse and unpredictable faults.

Diversity is known to be a major asset for the robustness of large, open, and complex systems (*e.g.*, economical or ecological systems). Following this observation, the software engineering literature provides a rich set of work that choose to implement diversity in software systems in order to improve robustness to attacks or to changes in quality of service. These works range from N-version programming to obfuscation of data structures or control flow, to randomization of instruction sets. An essential remaining challenge is to support the automatic synthesis and evolution of software diversity in open software-intensive systems. There is an opportunity to further enhance these techniques in order to cope with a wider diversity of faults, by multiplying the levels of diversity in the different software layers that are found in software-intensive systems (system, libraries, frameworks, application). This increased diversity must be based on artificial program transformations and code synthesis, which increase the chances of exploring novel solutions, better fitted at one point in time. The biological analogy also indicates that diversity should emerge as a side-effect of evolution, to prevent over-specialization towards one kind of diversity.

3.2.4.2. Scientific objectives

The main objective is to address one of the main limitations of N-version programming for fault-tolerant systems: the manual production and management of software diversity. Through automated injection of artificial diversity we aim at systematically increasing failure diversity and thus increasing the chances of early error detection at run-time. A fundamental assumption for this work is that software-intensive systems can be “good enough” [145], [157].

Proactive program diversification. We aim at establishing novel principles and techniques that favor the emergence of multiple forms of software diversity in software-intensive systems, in conjunction with the software adaptation mechanisms that leverage this diversity. The main expected outcome is a set of meta-design principles that maintain diversity in systems and the experimental demonstration of the effects of software diversity on the adaptive capacities of CASs. Higher levels of diversity in the system provide a pool of software solutions that can eventually be used to adapt to situations unforeseen at design time (bugs, crash, attacks, etc.). Principles of automated software diversification rely on the automated synthesis of variants in a software product line, as well as finer-grained program synthesis combining unsound transformations and genetic programming to explore the space of mutational robustness.

Multi-tier software diversification. We call multi-tier diversification the fact of diversifying several application software components simultaneously. The novelty of our proposal, with respect to the software diversity state of the art, is to diversify the application-level code (for example, diversify the business logics of the application), focusing on the technical layers found in web applications. The diversification of application software

code is expected to provide a diversity of failures and vulnerabilities in web server deployment. Web server deployment usually adopts a form of the Reactor architecture pattern, for scalability purposes: multiple copies of the server software stack, called request handlers, are deployed behind a load balancer. This architecture is very favorable for diversification, since by using the multiplicity of request handlers running in a web server we can simultaneously deploy multiple combinations of diverse software components. Then, if one handler is hacked or crashes the others should still be able to process client requests.

KerData Project-Team

3. Research Program

3.1. Our goals and methodology

Data-intensive applications demonstrate common requirements with respect to the need for data storage and I/O processing. These requirements lead to several core challenges discussed below.

Challenges related to cloud storage. In the area of cloud data management, a significant milestone is the emergence of the Map-Reduce [31] parallel programming paradigm, currently used on most cloud platforms, following the trend set up by Amazon [27]. At the core of Map-Reduce frameworks lies a key component, which must meet a series of specific requirements that have not fully been met yet by existing solutions: the ability to provide efficient *fine-grain access* to the files, while sustaining a *high throughput* in spite of *heavy access concurrency*. Additionally, as thousands of clients simultaneously access shared data, it is critical to preserve *fault-tolerance* and *security* requirements.

Challenges related to data-intensive HPC applications. The requirements exhibited by climate simulations specifically highlight a major, more general research topic. They have been clearly identified by international panels of experts like IESP [30], EESI [28], ETP4HPC [29] in the context of HPC simulations running on post-Petascale supercomputers. A jump of one order of magnitude in the size of numerical simulations is required to address some of the fundamental questions in several communities such as climate modeling, solid earth sciences or astrophysics. In this context, the lack of data-intensive infrastructures and methodologies to analyze huge simulations is a growing limiting factor. The challenge is to find new ways to store and analyze massive outputs of data during and after the simulation without impacting the overall performance.

The overall goal of the KerData project-team is to bring a substantial contribution to the effort of the research community to address the above challenges. KerData aims to design and implement distributed algorithms for scalable data storage and input/output management for efficient large-scale data processing. We target two main execution infrastructures: cloud platforms and post-Petascale HPC supercomputers. Additionally, we are also looking at other kinds of infrastructures, e.g. hybrid platforms combining enterprise desktop grids extended to cloud platforms. Our collaboration porfolio includes international teams that are active in this area both in Academia (e.g., Argonne National Lab, University of Illinois at Urbana-Champaign, Barcelona Supercomputing Centre) and Industry (Microsoft, IBM).

The highly experimental nature of our research validation methodology should be stressed. Our approach relies on building prototypes and on validating them at a large scale on real testbeds and experimental platforms. We strongly rely on the Grid'5000 platform. Moreover, thanks to our projects and partnerships, we have access to reference software and physical infrastructures in the cloud area (Microsoft Azure, Amazon clouds, Nimbus clouds); in the post-Petascale HPC area we have access to the Jaguar and Kraken supercomputers (ranked 3rd and 11th respectively in the Top 500 supercomputer list) and to the Blue Waters supercomputer. This provides us with excellent opportunities to validate our results on advanced realistic platforms.

Moreover, the consortiums of our current projects include application partners in the areas of Bio-Chemistry, Neurology and Genetics, and Climate Simulations. This is an additional asset, it enables us to take into account application requirements in the early design phase of our solutions, and to validate those solutions with real applications. We intend to continue increasing our collaborations with application communities, as we believe that this a key to perform effective research with a high impact.

3.2. Our research agenda

Three typical application scenarios will be described in detail in the next section:

- Joint genetic and neuroimaging data analysis on Azure clouds;
- Structural protein analysis on Nimbus clouds;
- I/O intensive climate simulations for the Blue Waters post-Petascale machine.

They illustrate the above challenges in some specific ways. They all exhibit a common scheme: massively concurrent processes which access massive data at a fine granularity, where data is shared and distributed at a large scale. To address the aforementioned challenges efficiently, we have started to work out an approach called BlobSeer, which stands today at the center of our research efforts. This approach relies on the design and implementation of *scalable* distributed algorithms for data storage and access. They combine advanced techniques for decentralized metadata and data management, with versioning-based concurrency control to optimize the performance of applications under heavy access concurrency.

Preliminary experiments with our BlobSeer BLOB management system within today's cloud software infrastructures proved very promising. Recently, we used the BlobSeer approach as a starting point to address two usage scenarios in more detail, which led to two more specific approaches: 1) Pyramid [35] (which borrows many concepts from BlobSeer), with a specific focus on array-oriented storage; and 2) Damaris (totally independent of BlobSeer), which exploits multicore parallelism in post-Petascale supercomputers. All these directions are described below.

Our short- and medium-term research plan is devoted to storage challenges in two main contexts: clouds and post-Petascale HPC architectures. Consequently, our research plan is split in two main themes, which correspond to their respective challenges. For each of those themes, we have initiated several actions through collaborative projects coordinated by KerData, which define our agenda for the next 4 years.

Based on very promising results demonstrated by BlobSeer in preliminary experiments [34], we have initiated several collaborative projects in the area of cloud data management, e.g., the MapReduce ANR project, the A-Brain Microsoft-Inria project, the Z-CloudFlow Microsoft-Inria project. Such frameworks are for us concrete and efficient means to work in close connection with strong partners already well positioned in the area of cloud computing research. Thanks to these projects, we have already started to enjoy a visible scientific positioning at the international level.

The particularly active Data@Exascale Associate Team creates the framework for an enlarged research activity involving a large number of young researchers and students. It serves as a basis for extended research activities based on our approaches, carried out beyond the frontiers of our team. In the HPC area, our presence in the research activities of the Joint UIUC-Inria Lab for Petascale Computing (JLPC) at Urbana-Champaign is a very exciting opportunity that we have started to leverage. It facilitates high-quality collaborations and access to some of the most powerful supercomputers, an important asset which already helped us produce and transfer some results, as described in Section 6.5 .

MYRIADS Project-Team

3. Research Program

3.1. Introduction

The research activity within the MYRIADS team encompasses several areas: distributed systems, middleware and programming models. We have chosen to provide a brief presentation of some of the scientific foundations associated with them: autonomic computing, future internet and SOA, distributed operating systems, and unconventional/nature-inspired programming.

3.2. Autonomic Computing

During the past years the development of raw computing power coupled with the proliferation of computer devices has grown at exponential rates. This phenomenal growth along with the advent of the Internet have led to a new age of accessibility — to other people, other applications and others systems. It is not just a matter of numbers. This boom has also led to unprecedented levels of complexity for the design and the implementation of these applications and systems, and of the way they work together. The increasing system scale is reaching a level beyond human ability to master its complexity.

This points towards an inevitable need to automate many of the functions associated with computing today. Indeed we want to interact with applications and systems intuitively, and we want to be far less involved in running them. Ideally, we would like computing systems to entirely manage themselves.

IBM [58] has named its vision for the future of computing "autonomic computing." According to IBM this new computer paradigm means the design and implementation of computer systems, software, storage and support that must exhibit the following basic fundamentals:

- **Flexibility.** An autonomic computing system must configure and reconfigure itself under varying, even unpredictable, conditions.
- **Accessibility.** The nature of the autonomic system is that it is always on.
- **Transparency.** The system will perform its tasks and adapt to a user's needs without dragging the user into the intricacies of its workings.

In the Myriads team we will act to satisfy these fundamentals.

3.3. Future Internet and SOA

Traditional information systems were built by integrating applications into a communication framework, such as CORBA or with an Enterprise Application Integration system (EAI). Today, companies need to be able to reconfigure themselves; they need to be able to include other companies' business, split or externalize some of their works very quickly. In order to do this, the information systems should react and adapt very efficiently. EAIs approaches did not provide the necessary agility because they were too tightly coupled and a large part of business processes were "hard wired" into company applications.

Web services and Service Oriented Architectures (SOA) partly provide agility because in SOA business processes are completely separated from applications which can only be viewed as providing services through an interface. With SOA technologies it is easily possible to modify business processes, change, add or remove services.

However, SOA and Web services technologies are mainly market-driven and sometimes far from the state-of-the-art of distributed systems. Achieving dependability or being able to guarantee Service Level Agreement (SLA) needs much more agility of software elements. Dynamic adaptability features are necessary at many different levels (business processes, service composition, service discovery and execution) and should be coordinated. When addressing very large scale systems, autonomic behaviour of services and other parts of service oriented architectures is necessary.

SOAs will be part of the "Future Internet". The "Future Internet" will encompass traditional Web servers and browsers to support company and people interactions (Internet of services), media interactions, search systems, etc. It will include many appliances (Internet of things). The key research domains in this area are network research, cloud computing, Internet of services and advanced software engineering.

The Myriads team will address adaptability and autonomy of SOAs in the context of Grids, Clouds and at large scale.

3.4. Distributed Operating Systems

An operating system provides abstractions such as files, processes, sockets to applications so that programmers can design their applications independently of the computer hardware. At execution time, the operating system is in charge of finding and managing the hardware resources necessary to implement these abstractions in a secure way. It also manages hardware and abstract resource sharing between different users and programs.

A distributed operating system makes a network of computers appear as a single machine. The structure of the network and the heterogeneity of the computation nodes are hidden to users. Members of the Myriads team members have a long experience in the design and implementation of distributed operating systems, for instance in Kerrighed, Vigne, and XtreemOS projects.

The cloud computing model [43], [40] introduces new challenges in the organization of the information infrastructure: security, identity management, adaptation to the environment (costs). The organization of large IT infrastructures is also impacted as their internal data-centers, sometimes called private clouds, need to cooperate with resources and services provisioned from the cloud in order to cope with workload variations. The advent of cloud and green computing introduces new challenges in the domain of distributed operating systems: resources can be provisioned and released dynamically, the distribution of the computations on the resources must be reevaluated periodically in order to reduce power consumption and resource usage costs. Distributed cloud operating system must adapt to these new challenges in order to reduce cost and energy, for instance, through the redistribution of the applications and services on a smaller set of resources.

The Myriads team works on the design and implementation of system services at IaaS and PaaS levels to autonomously manage cloud and cloud federations resources and support collaboration between cloud users.

3.5. Unconventional/Nature-inspired Programming

Levering the computing services available on the Internet requires to revisit programming models, with the idea of expressing decentralised and autonomous behaviours (in particular self-repairing, self-adaptation). More concretely, composing services within large scale platforms calls for mechanisms to adequately discover and select services at run time, upon failure, or unexpected results.

Nature metaphors have been shown to provide adequate abstractions to build autonomic systems. Firstly, we want to explore nature metaphors, such as the chemical programming model as alternative programming models for expressing the interactions and coordination of services at large scale to build applications dynamically.

Within the *chemical* paradigm, a program is seen as a solution in which molecules (data) float and react together to produce new data according to rules (programs). Such a paradigm, implicitly parallel and distributed, appears to be a good candidate to express high level interactions of software components. The language naturally focus on the coordination of distributed autonomous entities. Thus, our first objective is to extend the semantics of chemical programs, in order to model not only a distributed execution of a service coordination, but also, the interactions between the different *molecules* within the Internet of Services (users, companies, services, advertisements, requests, ...). At present, a distributed implementation of the chemical paradigm does not exist. Our second objective is to develop the concepts and techniques required for such an implementation. While the paradigm exhibit several limitations regarding its run-time complexity, revisiting the model and studying its implementation over distributed platforms, and then showing its relevance in concrete settings (such as service coordination) may constitute an innovative research area.

TACOMA Team

3. Research Program

3.1. Using and Programming Context

The goal of ambient computing is to seamlessly merge virtual and real environments. A real environment is composed of objects from the physical world, e.g., people, places, machines. A virtual environment is any information system, e.g., the Web. The integration of these environments must permit people and their information systems to implicitly interact with their surrounding environment.

Ambient computing applications are able to evaluate the state of the real world through sensing technologies. This information can include the position of a person (caught with a localization system like GPS), the weather (captured using specialized sensors), etc. Sensing technologies enable applications to automatically update digital information about events or entities in the physical world. Further, interfaces can be used to act on the physical world based on information processed in the digital environment. For example, the windows of a car can be automatically closed when it is raining.

This real-world and virtual-world integration must permit people to implicitly interact with their surrounding environment. This means that manual device manipulation must be minimal since this constrains person mobility. In any case, the relative small size of personal devices can make them awkward to manipulate. In the near future, interaction must be possible without people being aware of the presence of neighbouring processors.

Information systems require tools to *capture* data in its physical environment, and then to *interpret*, or process, this data. A context denotes all information that is pertinent to a person-centric application. There are three classes of context information:

- The *digital context* defines all parameters related to the hardware and software configuration of the device. Examples include the presence (or absence) of a network, the available bandwidth, the connected peripherals (printer, screen), storage capacity, CPU power, available executables, etc.
- The *personal context* defines all parameters related to the identity, preferences and location of the person who owns the device. This context is important for deciding the type of information that a personal device needs to acquire at any given moment.
- The *physical context* relates to the person's environment; this includes climatic condition, noise level, luminosity, as well as date and time.

All three forms of context are fundamental to person-centric computing. Consider for instance a virtual museum guide service that is offered via a PDA. Each visitor has his own PDA that permits him to receive and visualise information about surrounding artworks. In this application, the *pertinent* context of the person is made up of the artworks situated near the person, the artworks that interest him as well as the degree of specialisation of the information, i.e., if the person is an art expert, he will desire more detail than the occasional museum visitor.

There are two approaches to organising data in a real to virtual world mapping: a so-called *logical* approach and a *physical* approach. The logical approach is the traditional way, and involves storing all data relevant to the physical world on a service platform such as a centralised database. Context information is sent to a person in response to a request containing the person's location co-ordinates and preferences. In the example of the virtual museum guide, a person's device transmits its location to the server, which replies with descriptions of neighbouring artworks.

The main drawbacks of this approach are scalability and complexity. Scalability is a problem since we are evolving towards a world with billions of embedded devices; complexity is a problem since the majority of physical objects are unrelated, and no management body can cater for the integration of their data into a service platform. Further, the model of the physical world must be up to date, so the more dynamic a system, the more updates are needed. The services platform quickly becomes a potential bottleneck if it must deliver services to all people.

The physical approach does not rely on a digital model of the physical world. The service is computed wherever the person is located. This is done by spreading data onto the devices in the physical environment; there are a sufficient number of embedded systems with wireless transceivers around to support this approach. Each device manages and stores the data of its associated object. In this way, data are physically linked to objects, and there is no need to update a positional database when physical objects move since the data *physically* moves with them.

With the physical approach, computations are done on the personal and available embedded devices. Devices interact when they are within communication range. The interactions constitute delivery of service to the person. Returning to the museum example, data is directly embedded in a painting's frame. When the visitor's guide meets (connects) to a painting's devices, it receives the information about the painting and displays it.

3.2. Coupled objects

Integrity checking is an important concern in many activities, both in the real world and in the information society. The basic purpose is to verify that a set of objects, parts, components, people remains the same along some activity or process, or remains consistent against a given property (such as a part count).

In the real world, it is a common step in logistic: objects to be transported are usually checked by the sender (for their conformance to the recipient expectation), and at arrival by the recipient. When a school get a group of children to a museum, people responsible for the children will regularly check that no one is missing. Yet another common example is to check for our personal belongings when leaving a place, to avoid lost. While important, these verification are tedious, vulnerable to human errors, and often forgotten.

Because of these vulnerabilities, problems arise: E-commerce clients sometimes receive incomplete packages, valuable and important objects (notebook computers, passports etc.) get lost in airports, planes, trains, hotels, etc. with sometimes dramatic consequences.

While there are very few automatic solutions to improve the situation in the real world, integrity checking in the computing world is a basic and widely used mechanism: magnetic and optical storage devices, network communications are all using checksums and error checking code to detect information corruption, to name a few.

The emergence of ubiquitous computing and the rapid penetration of RFID devices enable similar integrity checking solutions to work for physical objects. We introduced the concept of *coupled object*, which offers simple yet powerful mechanisms to check and ensure integrity properties for set of physical objects.

Essentially, coupled objects are a set of physical objects which defines a logical group. An important feature is that the group information is self contained on the objects which allow to verify group properties, such as completeness, only with the objects. Said it another way, the physical objects can be seen as fragments of a composite object. A trivial example could be a group made of a person, his jacket, his mobile phone, his passport and his cardholder.

The important feature of the concept are its distributed, autonomous and anonymous nature: it allows the design and implementation of pervasive security applications without any database tracking or centralized information system support. This is a significant advantage of this approach given the strong privacy issues that affect pervasive computing.

DREAM Project-Team

3. Research Program

3.1. Introduction

The research agenda of the Dream project-team revolves around the following 4 main topics:

- Simulator-based decision support systems
- Incremental learning
- Mining complex patterns
- Answer Set Programming

3.2. Simulator-based decision support systems

A common way to investigate and understand complex phenomena, such as such as those related to ecosystems, consists in designing a computational model and implementing a simulator to test the system behavior under various parameters. These simulators enable a fine grained understanding of the system studied, however they produce huge quantities of data. To be able to exploit these simulators in decision support scenarios, it is thus critical to provide methods to simplify the interactions with the simulator and handle the large quantity of data produced.

- One approach is to store all the simulation data in a datawarehouse and provide scientists and experts with tools to analyze efficiently the simulation data. Providing users with means to dig through large amount of multidimensional data, from more or less abstract viewpoints, and express preferences on the returned results is an important research topic in databases and data mining. To this end, *Skyline queries* constitute a relevant approach as they retrieve the most interesting objects with respect to multi-dimensional criteria with the possibility of making compromises on conflicting dimensions. The challenge is to define and implement skyline queries in a datawarehouse context. In this field, we are investigating efficient interactive tools for answering dynamic [36] and hierarchical [10] skyline queries.
- Another approach is to simplify the simulation model. For some applications, the system is too complex for a traditional numerical simulation to give relevant results in a short amount of time. It is especially the case when data and knowledge are not available to supply numerical models. Qualitative models offers a good alternative to model complex systems in such context. This abstracted representation offers an efficient computation on model exploration and gives relevant results when querying the system behavior. In the Dream project-team we focused on qualitative models of dynamical systems described as Discrete Event Systems (DES). Recent studies have emphasized the great interest of coupling model-checking techniques with qualitative models. We propose to use the timed automata formalism that allow the explicit representation of time [29]. In this context, the research issues we investigate are the following.
  - The size of a global model constructed from an abstracted description of the system and domain knowledge is potentially huge. A challenging problem is to reduce the size of this model using artificial intelligence tools [37].
  - It is necessary to propose a high-level language to explore and predict future changes of the system. Using this language, a stakeholder should express easily any requirements he wants to ask on the system behavior. We investigate the formalization of query patterns relying on recent temporal logics that can be exploited using model-checking techniques [52].

  - Another challenge is the computation of the optimal strategy for a reachability problem (*"what is the best sequence of actions to reach a specific state at a specific time ?"*). In this case we propose to use extended timed automata, such as timed game automata or priced time automata, with controller synthesis methods [30].

- When modelling becomes increasingly complex because of ever-increasing numbers of combined processes, making model-based decision aids are essential. Our approach uses symbolic learning techniques on simulated data to synthetise complex processses and help in decision making. Thus rule induction has attracted a great deal of attention in Machine Learning and Data Mining. However generating rules is not an end in itself because their applicability is not straightforward, especially when their number is high.

  Our goal is to lighten the burden of analyzing a large set of classification rules when the user is confronted to an "unsatisfactory situation" and needs help to decide about the appropriate action to remedy to this situation. The method consists in comparing the situation to a set of classification rules. For this purpose, we have proposed a framework for learning action recommendations dealing with complex notions of feasibility and quality of actions [63].

3.3. Incremental learning

The first learning algorithms were batch learning. They examine all examples and produce a concept description, that is generally not further modified. This is not adapted to dynamic settings where data are delivered continuously. For such settings, incremental algorithms have been proposed. These algorithms examine the training example one at a time (or set by set), maintaining a "best-so-far" description which may be modified each time a new example (or set of examples) arrives. In order to strengthen the learning process, some specific old examples are often kept: this is called partial memory systems. A more specific classification of incremental learning can be found in [58].

Current issues in incremental learning are

- for partial instance memory: how to select examples, [56]
- the problem of hidden context: the target concept may depend of unknown variables, which are not given as explicit attributes [66]
- the problem of concept drift: the target changes with time [65], [39]
- the problem of masked example: the data distribution may change and some examples may not be anymore visible.

As a human expert has to give his opinion on the learned description model, we focus our research on incremental learning of rules ([39]).

3.4. Mining complex patterns

Pattern mining, a subdomain of data mining, is an unsupervised learning method which aims at discovering interesting knowledge from data. Association rule extraction is one of the most popular approach and has received a lot of interest in the last 20 years. For instance, many enhancements have been proposed to the well-known Apriori algorithm [27]. It is based on a level-wise generation of candidate patterns and on efficient candidate pruning having a sufficient relevance, usually related to the frequency of the candidate pattern in the data-set (i.e., the support): the most frequent patterns should be the most interesting. Later, Agrawal and Srikant proposed a framework for "mining sequential patterns" [28], which extends Apriori by coping with the order of elements in patterns. Such approach initiated research on *temporal pattern mining*, which is of particular interest for the DREAM team. The simplest temporal patterns are sequential patterns that constraints the order of the events in one of its occurrence. More advanced approaches also exploit quantitative information in order to provide significant patterns about both ordering and duration of events as well as inter-event delay. A challenge is that the classical anti-monotony property, used to prune the search space, is difficult to define in this case.

Many work in pattern mining have attempted to improve the runtime efficiency of algorithms, on the one hand, by proposing more efficient representation and execution schemes such as pattern-growth methods [48], or, on the other hand, by focusing on condensed representations such as closed patterns [60], [64]. Other research directions have been investigated to enhance the syntax of patterns e.g. temporal and periodic patterns, mutidimensional and hierarchical patterns, constrained patterns, contextual patterns, etc. Despite these improvements, the size of the results may still be too high. Thus, post-mining or visualization methods have been introduced to let the user focus on results that correspond to his own preferences.

Another challenge of pattern mining is that for each pattern mining task (such as mining itemsets, sequences or graphs) there are many specialized algorithms, each exploiting some ad-hoc optimizations. It is very hard for a practitioner to find an algorithm suited for his problem, and such an algorithm may not exist. There is a need to propose novel *generic* pattern mining algorithms, that exploit the main algorithmic advances proposed in the last 20 years, and that only require a description of their pattern mining problem from practioners. Recently, we have proposed ParaMiner [59], a generic pattern mining algorithm using state of the art optimizations and exploiting the parallelism of multicore processors. The practitioner only has to enter a pattern interest criteria and check that it verifies a *strong accessibility* property coming from set theory. As of now, ParaMiner is the fastest generic pattern mining algorithm, being competitive with specialized algorithm on several pattern mining tasks.

Other approaches propose a completely declarative way to specify the pattern mining problem. In this case, the most used framework is Constraint Programming [44]. We are investigating another approach based on *Answer Set Programming*.

3.5. Answer Set Programing (ASP)

The DREAM team is investigating declarative approaches to solve complex problems such as causal reasoning, landscape simultation and pattern mining. One such approach is ASP.

ASP (Answer set programming) [43], [31] is an approach to declarative problem solving, combining a rich yet simple modelling language with high-performance solving capacities, tailored to Knowledge Representation and Reasoning. "Declarative problem solving" means that the program is close to the way a problem is enunciated, and not to the way the problem is solved. This facilitates writing and revising programs. ASP is an outgrowth of research on the use of non monotonic reasoning in knowledge representation. ASP programs[23] consist in rules that look like Prolog rules, but the computational mechanism is different [54].

ASP allows to solve search problems in NP (and theoretically in NP^{NP}) in a uniform way (being more compact than boolean approaches like SAT solvers). ASP is good when dealing with knowledge representation, particularly when logical rules or graphs are involved. The versatility of ASP is reflected by the ASP solver clasp, winning first places at ASP, SAT and other competitions.

ASP solvers deal with propositional rules, however in practice predicates are allowed. A *grounder* replaces each free variable of the program provided by users with any eligible constant symbol. The output of the grounder is thus a propositional program, which is piped into a *solver* which then computes *answer sets*. These answer sets are the models for the ASP theory, and they constitute the result of an ASP program. The user may ask for all the models, or only one, or any number n of models. The most powerful version (clingo, which combines the grounder gringo and the solver clasp) is from Torsten Schaub's team (see http://potassco.sourceforge.net for the last version of clingo, including a *guide*). These versions can be easily interfaced with python programs, which extends further the practical applicability of ASP [42].

The main interests of using ASP are: 1) the ease to write and to update programs, and 2) the efficiency of the ASP solvers (improved in the recent versions).

Our main challenge is to propose ASP modeling that scales up to solving real problems. We are especially working on the modeling of sequential pattern mining with ASP in order to mine real datasets in a flexible and efficient way.

Our second challenge is to model a wide range of expert knowledge to include reasoning into the solving processes, in order to output more meaningful results.

HYBRID Project-Team

3. Research Program

3.1. Research Program

The scientific objective of Hybrid team is to improve 3D interaction of one or multiple users with virtual environments, by making full use of physical engagement of the body, and by incorporating the mental states by means of brain-computer interfaces. We intend to improve each component of this framework individually, but we also want to improve the subsequent combinations of these components.

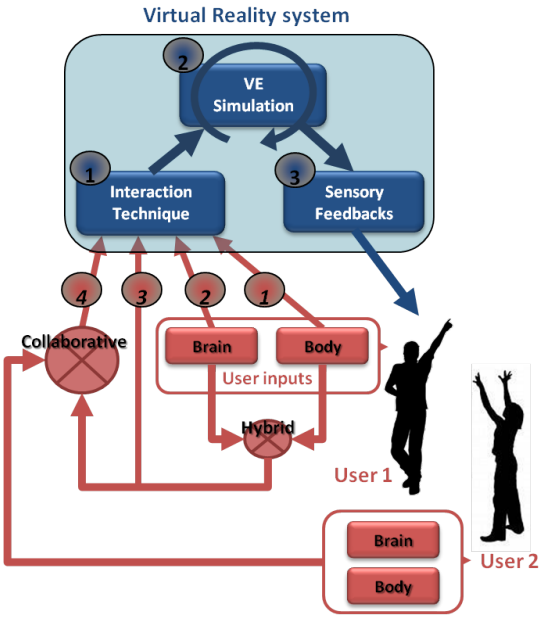


Figure 1. 3D hybrid interaction loop between one or multiple users and a virtual reality system. Top (in blue) three steps of 3D interaction with a virtual environment: (1) interaction technique, (2) simulation of the virtual environment, (3) sensory feedbacks. Bottom (in red) different cases of interaction: (1) body-based, (2) mind-based, (3) hybrid, and (4) collaborative 3D interaction.

The "hybrid" 3D interaction loop between one or multiple users and a virtual environment is depicted on Figure 1 . Different kinds of 3D interaction situations are distinguished (red arrows, bottom): 1) body-based interaction, 2) mind-based interaction, 3) hybrid and/or 4) collaborative interaction (with at least two users). In each case, three scientific challenges arise which correspond to the three successive steps of the 3D interaction loop (blue squares, top): 1) the 3D interaction technique, 2) the modeling and simulation of the 3D scenario, and 3) the design of appropriate sensory feedback.

The 3D interaction loop involves various possible inputs from the user(s) and different kinds of output (or sensory feedback) from the simulated environment. Each user can involve his/her body and mind by means of corporal and/or brain-computer interfaces. A hybrid 3D interaction technique (1) mixes mental and motor inputs and translates them into a command for the virtual environment. The real-time simulation (2) of the

virtual environment is taking into account these commands to change and update the state of the virtual world and virtual objects. The state changes are sent back to the user and perceived by means of different sensory feedbacks (e.g., visual, haptic and/or auditory) (3). The sensory feedbacks are closing the 3D interaction loop. Other users can also interact with the virtual environment using the same procedure, and can eventually "collaborate" by means of "collaborative interactive techniques" (4).

This description is stressing three major challenges which correspond to three mandatory steps when designing 3D interaction with virtual environments:

- **3D interaction techniques:** This first step consists in translating the actions or intentions of the user (inputs) into an explicit command for the virtual environment. In virtual reality, the classical tasks that require such kinds of user command were early categorized in four [49]: navigating the virtual world, selecting a virtual object, manipulating it, or controlling the application (entering text, activating options, etc). The addition of a third dimension, the use of stereoscopic rendering and the use of advanced VR interfaces make however inappropriate many techniques that proved efficient in 2D, and make it necessary to design specific interaction techniques and adapted tools. This challenge is here renewed by the various kinds of 3D interaction which are targeted. In our case, we consider various cases, with motor and/or cerebral inputs, and potentially multiple users.
- **Modeling and simulation of complex 3D scenarios:** This second step corresponds to the update of the state of the virtual environment, in real-time, in response to all the potential commands or actions sent by the user. The complexity of the data and phenomena involved in 3D scenarios is constantly increasing. It corresponds for instance to the multiple states of the entities present in the simulation (rigid, articulated, deformable, fluids, which can constitute both the user's virtual body and the different manipulated objects), and the multiple physical phenomena implied by natural human interactions (squeezing, breaking, melting, etc). The challenge consists here in modeling and simulating these complex 3D scenarios and meeting, at the same time, two strong constraints of virtual reality systems: performance (real-time and interactivity) and genericity (e.g., multi-resolution, multi-modal, multi-platform, etc).
- **Immersive sensory feedbacks:** This third step corresponds to the display of the multiple sensory feedbacks (output) coming from the various VR interfaces. These feedbacks enable the user to perceive the changes occurring in the virtual environment. They are closing the 3D interaction loop, making the user immersed, and potentially generating a subsequent feeling of presence. Among the various VR interfaces which have been developed so far we can stress two kinds of sensory feedback: visual feedback (3D stereoscopic images using projection-based systems such as CAVE systems or Head Mounted Displays); and haptic feedback (related to the sense of touch and to tactile or force-feedback devices). The Hybrid team has a strong expertize in haptic feedback, and in the design of haptic and "pseudo-haptic" rendering [50]. Note that a major trend in the community, which is strongly supported by the Hybrid team, relates to a "perception-based" approach, which aims at designing sensory feedbacks which are well in line with human perceptual capacities.

These three scientific challenges are addressed differently according to the context and the user inputs involved. We propose to consider three different contexts, which correspond to the three different research axes of the Hybrid research team, namely : 1) body-based interaction (motor input only), 2) mind-based interaction (cerebral input only), and then 3) hybrid and collaborative interaction (i.e., the mixing of body and brain inputs from one or multiple users).

3.2. Research Axes

The scientific activity of Hybrid team follows three main axes of research:

- **Body-based interaction in virtual reality.** Our first research axis concerns the design of immersive and effective "body-based" 3D interactions, i.e., relying on a physical engagement of the user's body. This trend is probably the most popular one in VR research at the moment. Most VR setups make use of tracking systems which measure specific positions or actions of the user in order to interact with a virtual environment. However, in recent years, novel options have emerged for measuring

"full-body" movements or other, even less conventional, inputs (e.g. body equilibrium). In this first research axis we are thus concerned by the emergence of new kinds of "body-based interaction" with virtual environments. This implies the design of novel 3D user interfaces and novel 3D interactive techniques, novel simulation models and techniques, and novel sensory feedbacks for body-based interaction with virtual worlds. It involves real-time physical simulation of complex interactive phenomena, and the design of corresponding haptic and pseudo-haptic feedback.

- **Mind-based interaction in virtual reality.** Our second research axis concerns the design of immersive and effective "mind-based" 3D interactions in Virtual Reality. Mind-based interaction with virtual environments is making use of Brain-Computer Interface technology. This technology corresponds to the direct use of brain signals to send "mental commands" to an automated system such as a robot, a prosthesis, or a virtual environment. BCI is a rapidly growing area of research and several impressive prototypes are already available. However, the emergence of such a novel user input is also calling for novel and dedicated 3D user interfaces. This implies to study the extension of the mental vocabulary available for 3D interaction with VE, then the design of specific 3D interaction techniques "driven by the mind" and, last, the design of immersive sensory feedbacks that could help improving the learning of brain control in VR.
- **Hybrid and collaborative 3D interaction.** Our third research axis intends to study the combination of motor and mental inputs in VR, for one or multiple users. This concerns the design of mixed systems, with potentially collaborative scenarios involving multiple users, and thus, multiple bodies and multiple brains sharing the same VE. This research axis therefore involves two interdependent topics: 1) collaborative virtual environments, and 2) hybrid interaction. It should end up with collaborative virtual environments with multiple users, and shared systems with body and mind inputs.

LAGADIC Project-Team

3. Research Program

3.1. Visual servoing

Basically, visual servoing techniques consist in using the data provided by one or several cameras in order to control the motions of a dynamic system [1]. Such systems are usually robot arms, or mobile robots, but can also be virtual robots, or even a virtual camera. A large variety of positioning tasks, or mobile target tracking, can be implemented by controlling from one to all the degrees of freedom of the system. Whatever the sensor configuration, which can vary from one on-board camera on the robot end-effector to several free-standing cameras, a set of visual features has to be selected at best from the image measurements available, allowing to control the desired degrees of freedom. A control law has also to be designed so that these visual features $\mathbf{s}(t)$ reach a desired value $\mathbf{s}^*$, defining a correct realization of the task. A desired planned trajectory $\mathbf{s}^*(t)$ can also be tracked. The control principle is thus to regulate to zero the error vector $\mathbf{s}(t) - \mathbf{s}^*(t)$. With a vision sensor providing 2D measurements, potential visual features are numerous, since 2D data (coordinates of feature points in the image, moments, ...) as well as 3D data provided by a localization algorithm exploiting the extracted 2D features can be considered. It is also possible to combine 2D and 3D visual features to take the advantages of each approach while avoiding their respective drawbacks.

More precisely, a set $\mathbf{s}$ of k visual features can be taken into account in a visual servoing scheme if it can be written:

$$\mathbf{s} = \mathbf{s}(\mathbf{x}(\mathbf{p}(t)), \mathbf{a}) \tag{33}$$

where $\mathbf{p}(t)$ describes the pose at the instant t between the camera frame and the target frame, $\mathbf{x}$ the image measurements, and $\mathbf{a}$ a set of parameters encoding a potential additional knowledge, if available (such as for instance a coarse approximation of the camera calibration parameters, or the 3D model of the target in some cases).

The time variation of $\mathbf{s}$ can be linked to the relative instantaneous velocity $\mathbf{v}$ between the camera and the scene:

$$\dot{\mathbf{s}} = \frac{\partial \mathbf{s}}{\partial \mathbf{p}} \dot{\mathbf{p}} = \mathbf{L}_{\mathbf{s}} \mathbf{v} \tag{34}$$

where $\mathbf{L}_{\mathbf{s}}$ is the interaction matrix related to $\mathbf{s}$. This interaction matrix plays an essential role. Indeed, if we consider for instance an eye-in-hand system and the camera velocity as input of the robot controller, we obtain when the control law is designed to try to obtain an exponential decoupled decrease of the error:

$$\mathbf{v}_c = -\lambda \widehat{\mathbf{L}_{\mathbf{s}}}^{+} (\mathbf{s} - \mathbf{s}^*) - \widehat{\mathbf{L}_{\mathbf{s}}}^{+} \widehat{\frac{\partial \mathbf{s}}{\partial t}} \tag{35}$$

where λ is a proportional gain that has to be tuned to minimize the time-to-convergence, $\widehat{\mathbf{L}_{\mathbf{s}}}^{+}$ is the pseudo-inverse of a model or an approximation of the interaction matrix, and $\widehat{\frac{\partial \mathbf{s}}{\partial t}}$ an estimation of the features velocity due to a possible own object motion.

From the selected visual features and the corresponding interaction matrix, the behavior of the system will have particular properties as for stability, robustness with respect to noise or to calibration errors, robot 3D trajectory, etc. Usually, the interaction matrix is composed of highly non linear terms and does not present any decoupling properties. This is generally the case when $\mathbf{s}$ is directly chosen as $\mathbf{x}$. In some cases, it may lead to inadequate robot trajectories or even motions impossible to realize, local minimum, tasks singularities, etc. It is thus extremely important to design adequate visual features for each robot task or application, the ideal case (very difficult to obtain) being when the corresponding interaction matrix is constant, leading to a simple linear control system. To conclude in few words, **visual servoing is basically a non linear control problem. Our Holy Grail quest is to transform it into a linear control problem.**

Furthermore, embedding visual servoing in the task function approach allows solving efficiently the redundancy problems that appear when the visual task does not constrain all the degrees of freedom of the system. It is then possible to realize simultaneously the visual task and secondary tasks such as visual inspection, or joint limits or singularities avoidance. This formalism can also be used for tasks sequencing purposes in order to deal with high level complex applications.

3.2. Visual tracking

Elaboration of object tracking algorithms in image sequences is an important issue for researches and applications related to visual servoing and more generally for robot vision. A robust extraction and real time spatio-temporal tracking process of visual cues is indeed one of the keys to success of a visual servoing task. If fiducial markers may still be useful to validate theoretical aspects in modeling and control, natural scenes with non cooperative objects and subject to various illumination conditions have to be considered for addressing large scale realistic applications.

Most of the available tracking methods can be divided into two main classes: feature-based and model-based. The former approach focuses on tracking 2D features such as geometrical primitives (points, segments, circles,...), object contours, regions of interest...The latter explicitly uses a model of the tracked objects. This can be either a 3D model or a 2D template of the object. This second class of methods usually provides a more robust solution. Indeed, the main advantage of the model-based methods is that the knowledge about the scene allows improving tracking robustness and performance, by being able to predict hidden movements of the object, detect partial occlusions and acts to reduce the effects of outliers. The challenge is to build algorithms that are fast and robust enough to meet our applications requirements. Therefore, even if we still consider 2D features tracking in some cases, our researches mainly focus on real-time 3D model-based tracking, since these approaches are very accurate, robust, and well adapted to any class of visual servoing schemes. Furthermore, they also meet the requirements of other classes of application, such as augmented reality.

3.3. Slam

Most of the applications involving mobile robotic systems (ground vehicles, aerial robots, automated submarines,...) require a reliable localization of the robot in its environment. A challenging problem is when neither the robot localization nor the map is known. Localization and mapping must then be considered concurrently. This problem is known as Simultaneous Localization And Mapping (Slam). In this case, the robot moves from an unknown location in an unknown environment and proceeds to incrementally build up a navigation map of the environment, while simultaneously using this map to update its estimated position.

Nevertheless, solving the Slam problem is not sufficient for guaranteeing an autonomous and safe navigation. The choice of the representation of the map is, of course, essential. The representation has to support the different levels of the navigation process: motion planning, motion execution and collision avoidance and, at the global level, the definition of an optimal strategy of displacement. The original formulation of the Slam problem is purely metric (since it basically consists in estimating the Cartesian situations of the robot and a set of landmarks), and it does not involve complex representations of the environment. However, it is now well recognized that **several complementary representations are needed to perform exploration, navigation, mapping, and control tasks successfully. We propose to use composite models of the environment that**

mix topological, metric, and grid-based representations. Each type of representation is well adapted to a particular aspect of autonomous navigation: the metric model allows one to locate the robot precisely and plan Cartesian paths, the topological model captures the accessibility of different sites in the environment and allows a coarse localization, and finally the grid representation is useful to characterize the free space and design potential functions used for reactive obstacle avoidance. However, ensuring the consistency of these various representations during the robot exploration, and merging observations acquired from different viewpoints by several cooperative robots, are difficult problems. This is particularly true when different sensing modalities are involved. New studies to derive efficient algorithms for manipulating the hybrid representations (merging, updating, filtering...) while preserving their consistency are needed.

LINKMEDIA Project-Team

3. Research Program

3.1. Scientific background

LINKMEDIA is a multidisciplinary research team, with multimedia data as the main object of study. We are guided by the data and their specificity—semantically interpretable, heterogeneous and multimodal, available in large amounts, unstructured and disconnected—, as well as by the related problems and applications.

With multimedia data at the center, orienting our choices of methods and algorithms and serving as a basis for experimental validation, the team is directly contributing to the following scientific fields:

- multimedia: content-based analysis; multimodal processing and fusion; multimedia applications;
- computer vision: compact description of images; object and event detection;
- natural language processing: topic segmentation; information extraction;
- information retrieval: high-dimensional indexing; approximate k-nn search; efficient set comparison;

LINKMEDIA also takes advantage of advances in the following fields, adapting recent developments to the multimedia area:

- signal processing – image processing; compression;
- machine learning – deep architectures; structured learning; adversarial learning;
- security – data encryption; differential privacy;
- data mining – time series mining and alignment; pattern discovery; knowledge extraction;

3.2. Workplan

Research activities in LINKMEDIA are organized along three major lines of research which build upon the scientific domains already mentioned.

3.2.1. Unsupervised motif discovery

As an alternative to supervised learning techniques, unsupervised approaches have emerged recently with the goal of discovering directly patterns and events of interest from the data, in a totally unsupervised manner. In the absence of prior knowledge on what we are interested in, meaningfulness can be judged based on one of three main criteria: unexpectedness, saliency and recurrence. This last case posits that repeating patterns, known as motifs, are potentially meaningful, leading to recent work on the unsupervised discovery of motifs in multimedia data [77], [75], [76].

LINKMEDIA seeks to *develop unsupervised motif discovery approaches which are both accurate and scalable*. In particular, we consider the discovery of repeating objects in image collections and the discovery of repeated sequences in video and audio streams. Research activities are organized along the following lines:

- developing the scientific basis for scalable motif discovery: sparse histogram representations; efficient co-occurrence counting; geometry and time aware indexing schemes;
- designing and evaluating accurate and scalable motif discovery algorithms applied to a variety of multimedia content: exploiting efficient geometry or time aware matching functions; fast approximate DTW; symbolic representations of multimedia data, in conjunction with existing symbolic data mining approaches;
- developing methodology for the interpretation, exploitation and evaluation of motif discovery algorithms in various use-cases: image classification; video stream monitoring; transcript-free NLP for spoken document;

3.2.2. Describing and structuring

Content-based analysis has received a lot of attention from the early days of multimedia, with an extensive use of supervised machine learning for all modalities [78], [72]. Progress in large scale entity and event recognition in multimedia content has made available general purpose approaches able to learn from very large data sets and performing fairly decently in a large number of cases. Current solutions are however limited to simple, homogeneous, information and can hardly handle structured information such as hierarchical descriptions, tree-structured or nested concepts.

LINKMEDIA aims at *expanding techniques for multimedia content modeling, event detection and structure analysis*. The main transverse research lines that LINKMEDIA will develop are as follows:

- context-aware content description targeting (homogeneous) collections of multimedia data: latent variable discovery; deep feature learning; motif discovery;
- secure description to enable privacy and security aware multimedia content processing: everaging encryption and diversity; exploring adversarial machine learning in a multimedia context; privacy-oriented image processing;
- multilevel modeling with a focus on probabilistic modeling of structured multimodal data: multiple kernels; structured machine learning; conditionnal random fields;

3.2.3. Linking

Creating explicit links between media content items has been considered on different occasions, with the goal of seeking and discovering information by browsing, as opposed to information retrieval via ranked lists of relevant documents. Content-based link creation has been initially addressed in the hypertext community for well-structured texts [71] and was recently extended to multimedia content [79], [74], [73]. The problem of organizing collections with links remains mainly unsolved for large heterogeneous collections of unstructured documents, with many issues deserving attention: linking at a fine semantic grain; selecting relevant links; characterizing links; evaluating links; etc.

LINKMEDIA targets pioneering research on media linking by **developing scientific ground, methodology and technology for content-based media linking** directed to applications exploiting rich linked content such as navigation or recommendation. Contributions are concentrated along the following lines:

- algorithmic of linked media for content-based link authoring in multimedia collections: time-aware graph construction; multimodal hypergraphs; large scale k-nn graphs;
- link interpretation and characterization to provide links semantics for interpretability: text alignment; entity linking; intention vs. extension;
- linked media usage and evaluation: information retrieval; summarization; data models for navigation; link prediction;

MIMETIC Project-Team

3. Research Program

3.1. Biomechanics and Motion Control

Human motion control is a very complex phenomenon that involves several layered systems, as shown in Figure 3 . Each layer of this controller is responsible for dealing with perceptual stimuli in order to decide the actions that should be applied to the human body and his environment. Due to the intrinsic complexity of the information (internal representation of the body and mental state, external representation of the environment) used to perform this task, it is almost impossible to model all the possible states of the system. Even for simple problems, there generally exist infinity of solutions. For example, from the biomechanical point of view, there are much more actuators (i.e. muscles) than degrees of freedom leading to infinity of muscle activation patterns for a unique joint rotation. From the reactive point of view there exist infinity of paths to avoid a given obstacle in navigation tasks. At each layer, the key problem is to understand how people select one solution among these infinite state spaces. Several scientific domains have addressed this problem with specific points of view, such as physiology, biomechanics, neurosciences and psychology.

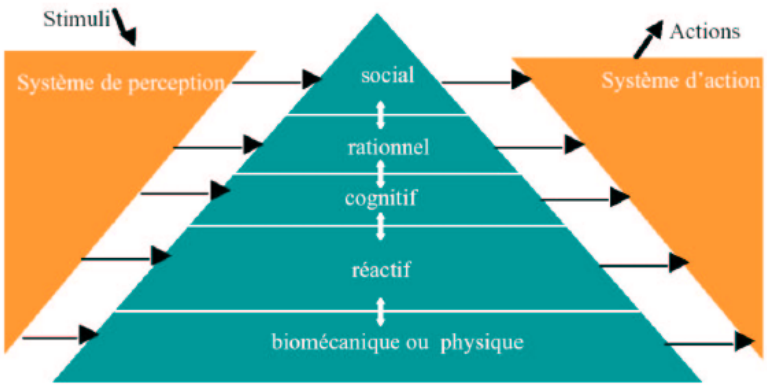


Figure 3. Layers of the motion control natural system in humans.

In biomechanics and physiology, researchers have proposed hypotheses based on accurate joint modeling (to identify the real anatomical rotational axes), energy minimization, force and torques minimization, comfort maximization (i.e. avoiding joint limits), and physiological limitations in muscle force production. All these constraints have been used in optimal controllers to simulate natural motions. The main problem is thus to define how these constraints are composed altogether such as searching the weights used to linearly combine these criteria in order to generate a natural motion. Musculoskeletal models are stereotyped examples for which there exist infinity of muscle activation patterns, especially when dealing with antagonist muscles. An unresolved problem is to define how using the above criteria to retrieve the actual activation patterns while optimization approaches still lead to unrealistic ones. It is still an open problem that will require multidisciplinary skills including computer simulation, constraint solving, biomechanics, optimal control, physiology and neurosciences.

In neuroscience, researchers have proposed other theories, such as coordination patterns between joints driven by simplifications of the variables used to control the motion. The key idea is to assume that instead of controlling all the degrees of freedom, people control higher level variables which correspond to combination of joint angles. In walking, data reduction techniques such as Principal Component Analysis have shown that lower-limb joint angles are generally projected on a unique plan whose angle in the state space is associated with energy expenditure. Although there exist knowledge on specific motion, such as locomotion or grasping, this type of approach is still difficult to generalize. The key problem is that many variables are coupled and it is very difficult to objectivly study the behavior of a unique variable in various motor tasks. Computer simulation is a promising method to evaluate such type of assumptions as it enables to accurately control all the variables and to check if it leads to natural movements.

Neurosciences also address the problem of coupling perception and action by providing control laws based on visual cues (or any other senses), such as determining how the optical flow is used to control direction in navigation tasks, while dealing with collision avoidance or interception. Coupling of the control variables is enhanced in this case as the state of the body is enriched by the big amount of external information that the subject can use. Virtual environments inhabited with autonomous characters whose behavior is driven by motion control assumptions is a promising approach to solve this problem. For example, an interesting problem in this field is navigation in an environment inhabited with other people. Typically, avoiding static obstacles together with other people displacing into the environment is a combinatory problem that strongly relies on the coupling between perception and action.

One of the main objectives of MimeTIC is to enhanche knowledge on human motion control by developing innovative experiments based on computer simulation and immersive environments. To this end, designing experimental protocols is a key point and some of the researchers in MimeTIC have developed this skill in biomechanics and perception-action coupling. Associating these researchers to experts in virtual human simulation, computational geometry and constraints solving enable us to contribute to enhance fundamental knowleged in human motion control.

3.2. Experiments in Virtual Reality

Understanding interaction between humans is very challenging because it addresses many complex phenomena including perception, decision-making, cognition and social behaviors. Moreover, all these phenomena are difficult to isolate in real situations, it is thus very complex to understand the influence of each of them on the interaction. It is then necessary to find an alternative solution that can standardize the experiments and that allows the modification of only one parameter at a time. Video was first used since the displayed experiment is perfectly repeatible and cut-offs (stop the video at a specific time before its end) allow having temporal information. Nevertheless, the absence of adapted viewpoint and stereoscopic vision does not provide depth information that are very meaningful. Moreover, during video recording session, the real human is acting in front of a camera and not an opponent. The interaction is then not a real interaction between humans.

Virtual Reality (VR) systems allow full standardization of the experimental situations and the complete control of the virtual environment. It is then possible to modify only one parameter at a time and observe its influence on the perception of the immersed subject. VR can then be used to understand what information are picked up to make a decision. Moreover, cut-offs can also be used to obtain temporal information about when these information are picked up. When the subject can moreover react as in real situation, his movement (captured in real time) provides information about his reactions to the modified parameter. Not only is the perception studied, but the complete perception-action loop. Perception and action are indeed coupled and influence each other as suggested by Gibson in 1979.

Finally, VR allows the validation of the virtual human models. Some models are indeed based on the interaction between the virtual character and the other humans, such as a walking model. In that case, there are two ways to validate it. First, they can be compared to real data (e.g. real trajectories of pedestrians). But such data are not always available and are difficult to get. The alternative solution is then to use VR. The validation of the realism of the model is then done by immersing a real subject in a virtual environment in which a virtual

character is controlled by the model. Its evaluation is then deduced from how the immersed subject reacts when interacting with the model and how realistic he feels the virtual character is.

3.3. Computational Geometry

Computational geometry is a branch of computer science devoted to the study of algorithms which can be stated in terms of geometry. It aims at studying algorithms for combinatorial, topological and metric problems concerning sets of points in Euclidian spaces. Combinatorial computational geometry focuses on three main problem classes: static problems, geometric query problems and dynamic problems.

In static problems, some input is given and the corresponding output needs to be constructed or found. Such problems include linear programming, Delaunay triangulations, and Euclidian shortest paths for instance. In geometric query problems, commonly known as geometric search problems, the input consists of two parts: the search space part and the query part, which varies over the problem instances. The search space typically needs to be preprocessed, in a way that multiple queries can be answered efficiently. Some typical problems are range searching, point location in a portioned space, nearest neighbor queries for instance. In dynamic problems, the goal is to find an efficient algorithm for finding a solution repeatedly after each incremental modification of the input data (addition, deletion or motion of input geometric elements). Algorithms for problems of this type typically involve dynamic data structures. Both of previous problem types can be converted into a dynamic problem, for instance, maintaining a Delaunay triangulation between moving points.

The Mimetic team works on problems such as crowd simulation, spatial analysis, path and motion planning in static and dynamic environments, camera planning with visibility constraints for instance. The core of those problems, by nature, relies on problems and techniques belonging to computational geometry. Proposed models pay attention to algorithms complexity to be compatible with performance constraints imposed by interactive applications.

PANAMA Project-Team

3. Research Program

3.1. Axis 1: sparse models and representations

3.1.1. Efficient sparse models and dictionary design for large-scale data

Sparse models are at the core of many research domains where the large amount and high-dimensionality of digital data requires concise data descriptions for efficient information processing. Recent breakthroughs have demonstrated the ability of these models to provide concise descriptions of complex data collections, together with algorithms of provable performance and bounded complexity.

A crucial prerequisite for the success of today's methods is the knowledge of a "dictionary" characterizing how to concisely describe the data of interest. Choosing a dictionary is currently something of an "art", relying on expert knowledge and heuristics.

Pre-chosen dictionaries such as wavelets, curvelets or Gabor dictionaries, are based upon stylized signal models and benefit from fast transform algorithms, but they fail to fully describe the content of natural signals and their variability. They do not address the huge diversity underlying modern data much beyond time series and images: data defined on graphs (social networks, internet routing, brain connectivity), vector valued data (diffusion tensor imaging of the brain), multichannel or multi-stream data (audiovisual streams, surveillance networks, multimodal biomedical monitoring).

The alternative to a pre-chosen dictionary is a trained dictionary learned from signal instances. While such representations exhibit good performance on small-scale problems, they are currently limited to low dimensional signal processing due to the necessary training data, memory requirements and computational complexity. Whether designed or learned from a training corpus, dictionary-based sparse models and the associated methodology fail to scale up to the volume and resolution of modern digital data, for they intrinsically involve difficult linear inverse problems. To overcome this bottleneck, a new generation of efficient sparse models is needed, beyond dictionaries, which will encompass the ability to provide sparse and structured data representations as well as computational efficiency. For example, while dictionaries describe low-dimensional signal models in terms of their "synthesis" using few elementary building blocks called atoms, in "analysis" alternatives the low-dimensional structure of the signal is rather "carved out" by a set of equations satisfied by the signal. Linear as well as nonlinear models can be envisioned.

3.1.2. Compressive Learning

A flagship emerging application of sparsity is the paradigm of compressive sensing, which exploits sparse models at the analog and digital levels for the acquisition, compression and transmission of data using limited resources (fewer/less expensive sensors, limited energy consumption and transmission bandwidth, etc.). Besides sparsity, a key pillar of compressive sensing is the use of random low-dimensional projections. Through compressive sensing, random projections have shown their potential to allow drastic dimension reduction with controlled information loss, provided that the projected signal vector admits a sparse representation in some transformed domain. A related scientific domain, where sparsity has been recognized as a key enabling factor, is Machine Learning, where the overall goal is to design statistically founded principles and efficient algorithms in order to infer general properties of large data collections through the observation of a limited number of representative examples. Marrying sparsity and random low-dimensional projections with machine learning shall allow the development of techniques able to efficiently capture and process the information content of large data collections. The expected outcome is a dramatic increase of the impact of sparse models in machine learning, as well as an integrated framework from the signal level (signals and their acquisition) to the semantic level (information and its manipulation), and applications to data sizes and volumes of collections that cannot be handled by current technologies.

3.2. Axis 2: robust acoustic scene analysis

3.2.1. Compressive acquisition and processing of acoustic scenes

Acoustic imaging and scene analysis involve acquiring the information content from acoustic fields with a limited number of acoustic sensors. A full 3D+t field at CD quality and Nyquist spatial sampling represents roughly 10^6 microphones/m^3. Dealing with such high-dimensional data requires to drastically reduce the data flow by positioning appropriate sensors, and selecting from all spatial locations the few spots where acoustic sources are active. The main goal is to develop a theoretical and practical understanding of the conditions under which compressive acoustic sensing is both feasible and robust to inaccurate modeling, noisy measures, and partially failing or uncalibrated sensing devices, in various acoustic sensing scenarii. This requires the development of adequate algorithmic tools, numerical simulations, and experimental data in simple settings where hardware prototypes can be implemented.

3.2.2. Robust audio source separation

Audio signal separation consists in extracting the individual sound of different instruments or speakers that were mixed on a recording. It is now successfully addressed in the academic setting of linear instantaneous mixtures. Yet, real-life recordings, generally associated to reverberant environments, remain an unsolved difficult challenge, especially with many sources and few audio channels. Much of the difficulty comes from the combination of (i) complex source characteristics, (ii) sophisticated underlying mixing model and (iii) adverse recording environments. Moreover, as opposed to the "academic" blind source separation task, most applicative contexts and new interaction paradigms offer a variety of situations in which prior knowledge and adequate interfaces enable the design and the use of informed and/or manually assisted source separation methods.

The former METISS team has developed a generic and flexible probabilistic audio source separation framework that has the ability to combine various acoustic models such as spatial and spectral source models. A first objective is to instantiate and validate specific instances of this framework targeted to real-world industrial applications, such as 5.1 movie re-mastering, interactive music soloist control and outdoor speech enhancement. Extensions of the framework are needed to achieve real-time online processing, and advanced constraints or probabilistic priors for the sources at hand will be designed, while paying attention to computational scalability issues.

In parallel to these efforts, expected progress in sparse modeling for inverse problems shall bring new approaches to source separation and modeling, as well as to source localization, which is often an important first step in a source separation workflow. In particular, a research avenue consists in investigating physically motivated, lower-level source models, notably through sparse analysis of sound waves. This should be complementary with the modeling of non-point sources and sensors, and a widening of the notion of "source localization" to the case of extended sources (i.e., considering problems such as the identification of the directivity of the source as well as its spatial position), with a focus on boundary conditions identification. A general perspective is to investigate the relations between the physical structure of the source and the particular structures that can be discovered or enforced in the representations and models used for characterization, localization and separation.

3.3. Axis 3: large-scale audio content processing and self-organization

3.3.1. Motif discovery in audio data

Facing the ever-growing quantity of multimedia content, the topic of motif discovery and mining has become an emerging trend in multimedia data processing with the ultimate goal of developing weakly supervised paradigms for content-based analysis and indexing. In this context, speech, audio and music content, offers a particularly relevant information stream from which meaningful information can be extracted to create some form of "audio icons" (key-sounds, jingles, recurrent locutions, musical choruses, etc ...) without resorting to comprehensive inventories of expected patterns.

This challenge raises several fundamental questions that will be among our core preoccupations over the next few years. The first question is the deployment of motif discovery on a large scale, a task that requires extending audio motif discovery approaches to incorporate efficient time series pattern matching methods (fingerprinting, similarity search indexing algorithms, stochastic modeling, etc.). The second question is that of the use and interpretation of the motifs discovered. Linking motif discovery and symbolic learning techniques, exploiting motif discovery in machine learning are key research directions to enable the interpretation of recurring motifs.

On the application side, several use cases can be envisioned which will benefit from motif discovery deployed on a large scale. For example, in spoken content, word-like repeating fragments can be used for several spoken document-processing tasks such as language-independent topic segmentation or summarization. Recurring motifs can also be used for audio summarization of audio content. More fundamentally, motif discovery paves the way for a shift from supervised learning approaches for content description to unsupervised paradigms where concepts emerge from the data.

3.3.2. Structure modeling and inference in audio and musical contents

Structuring information is a key step for the efficient description and learning of all types of contents, and in particular audio and musical contents. Indeed, structure modeling and inference can be understood as the task of detecting dependencies (and thus establishing relationships) between different fragments, parts or sections of information content.

A stake of structure modeling is to enable more robust descriptions of the properties of the content and better model generalization abilities that can be inferred from a particular content, for instance via cache models, trigger models or more general graphical models designed to render the information gained from structural inference. Moreover, the structure itself can become a robust descriptor of the content, which is likely to be more resistant than surface information to a number of operations such as transmission, transduction, copyright infringement or illegal use.

In this context, information theory concepts will be investigated to provide criteria and paradigms for detecting and modeling structural properties of audio contents, covering potentially a wide range of application domains in speech content mining, music modeling or audio scene monitoring.

SIROCCO Project-Team

3. Research Program

3.1. Introduction

The research activities on analysis, compression and communication of visual data mostly rely on tools and formalisms from the areas of statistical image modelling, of signal processing, of coding and information theory. However, the objective of better exploiting the Human Visual System (HVS) properties in the above goals also pertains to the areas of perceptual modelling and cognitive science. Some of the proposed research axes are also based on scientific foundations of computer vision (e.g. multi-view modelling and coding). We have limited this section to some tools which are central to the proposed research axes, but the design of complete compression and communication solutions obviously rely on a large number of other results in the areas of motion analysis, transform design, entropy code design, etc which cannot be all described here.

3.2. Parameter estimation and inference

Bayesian estimation, Expectation-Maximization, stochastic modelling

Parameter estimation is at the core of the processing tools studied and developed in the team. Applications range from the prediction of missing data or future data, to extracting some information about the data in order to perform efficient compression. More precisely, the data are assumed to be generated by a given stochastic data model, which is partially known. The set of possible models translates the a priori knowledge we have on the data and the best model has to be selected in this set. When the set of models or equivalently the set of probability laws is indexed by a parameter (scalar or vectorial), the model is said parametric and the model selection resorts to estimating the parameter. Estimation algorithms are therefore widely used at the encoder in order to analyze the data. In order to achieve high compression rates, the parameters are usually not sent and the decoder has to jointly select the model (i.e. estimate the parameters) and extract the information of interest.

3.3. Data Dimensionality Reduction

Manifolds, locally linear embedding, non-negative matrix factorization, principal component analysis

A fundamental problem in many data processing tasks (compression, classification, indexing) is to find a suitable representation of the data. It often aims at reducing the dimensionality of the input data so that tractable processing methods can then be applied. Well-known methods for data dimensionality reduction include principal component analysis (PCA) and independent component analysis (ICA). The methodologies which will be central to several proposed research problems will instead be based on sparse representations, on locally linear embedding (LLE) and on the "non negative matrix factorization" (NMF) framework.

The objective of *sparse representations* is to find a sparse approximation of a given input data. In theory, given $A \in \mathbb{R}^{m \times n}$, $m < n$, and $\mathbf{b} \in \mathbb{R}^m$ with $m << n$ and A is of full rank, one seeks the solution of $\min\{\|\mathbf{x}\|_0 \ : \ A\mathbf{x} = \mathbf{b}\}$, where $\|\mathbf{x}\|_0$ denotes the L_0 norm of x, i.e. the number of non-zero components in z. There exist many solutions x to $Ax = b$. The problem is to find the sparsest, the one for which x has the fewest non zero components. In practice, one actually seeks an approximate and thus even sparser solution which satisfies $\min\{\|\mathbf{x}\|_0 \ : \ \|A\mathbf{x} - \mathbf{b}\|_p \leq \rho\}$, for some $\rho \geq 0$, characterizing an admissible reconstruction error. The norm p is usually 2, but could be 1 or ∞ as well. Except for the exhaustive combinatorial approach, there is no known method to find the exact solution under general conditions on the dictionary A. Searching for this sparsest representation is hence unfeasible and both problems are computationally intractable. Pursuit algorithms have been introduced as heuristic methods which aim at finding approximate solutions to the above problem with tractable complexity.

Non negative matrix factorization (NMF) is a non-negative approximate data representation [0]. NMF aims at finding an approximate factorization of a non-negative input data matrix V into non-negative matrices W and H, where the columns of W can be seen as *basis vectors* and those of H as coefficients of the linear approximation of the input data. Unlike other linear representations like PCA and ICA, the non-negativity constraint makes the representation purely additive. Classical data representation methods like PCA or Vector Quantization (VQ) can be placed in an NMF framework, the differences arising from different constraints being placed on the W and H matrices. In VQ, each column of H is constrained to be unitary with only one non-zero coefficient which is equal to 1. In PCA, the columns of W are constrained to be orthonormal and the rows of H to be orthogonal to each other. These methods of data-dependent dimensionality reduction will be at the core of our visual data analysis and compression activities.

3.4. Perceptual Modelling

Saliency, visual attention, cognition

The human visual system (HVS) is not able to process all visual information of our visual field at once. To cope with this problem, our visual system must filter out irrelevant information and reduce redundant information. This feature of our visual system is driven by a selective sensing and analysis process. For instance, it is well known that the greatest visual acuity is provided by the fovea (center of the retina). Beyond this area, the acuity drops down with the eccentricity. Another example concerns the light that impinges on our retina. Only the visible light spectrum lying between 380 nm (violet) and 760 nm (red) is processed. To conclude on the selective sensing, it is important to mention that our sensitivity depends on a number of factors such as the spatial frequency, the orientation or the depth. These properties are modeled by a sensitivity function such as the Contrast Sensitivity Function (CSF).

Our capacity of analysis is also related to our visual attention. Visual attention which is closely linked to eye movement (note that this attention is called *overt* while the covert attention does not involve eye movement) allows us to focus our biological resources on a particular area. It can be controlled by both top-down (i.e. goal-directed, intention) and bottom-up (stimulus-driven, data-dependent) sources of information [0]. This detection is also influenced by prior knowledge about the environment of the scene [0]. Implicit assumptions related to prior knowledge or beliefs play an important role in our perception (see the example concerning the assumption that light comes from above-left). Our perception results from the combination of prior beliefs with data we gather from the environment. A Bayesian framework is an elegant solution to model these interactions [0]. We define a vector $\overrightarrow{v}_l$ of local measurements (contrast of color, orientation, etc.) and vector $\overrightarrow{v}_c$ of global and contextual features (global features, prior locations, type of the scene, etc.). The salient locations S for a spatial position $\overrightarrow{x}$ are then given by:

$$S(\overrightarrow{x}) = \frac{1}{p(\overrightarrow{v}_l \,|\, \overrightarrow{v}_c)} \times p(s, \overrightarrow{x} \,|\, \overrightarrow{v}_c) \tag{36}$$

The first term represents the bottom-up salience. It is based on a kind of contrast detection, following the assumption that rare image features are more salient than frequent ones. Most of existing computational models of visual attention rely on this term. However, different approaches exist to extract the local visual features as well as the global ones. The second term is the contextual priors. For instance, given a scene, it indicates which parts of the scene are likely the most salient.

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3.5. Coding theory

OPTA limit (Optimum Performance Theoretically Attainable), Rate allocation, Rate-Distortion optimization, lossy coding, joint source-channel coding multiple description coding, channel modelization, oversampled frame expansions, error correcting codes.

Source coding and channel coding theory [0] is central to our compression and communication activities, in particular to the design of entropy codes and of error correcting codes. Another field in coding theory which has emerged in the context of sensor networks is Distributed Source Coding (DSC). It refers to the compression of correlated signals captured by different sensors which do not communicate between themselves. All the signals captured are compressed independently and transmitted to a central base station which has the capability to decode them jointly. DSC finds its foundation in the seminal Slepian-Wolf [0] (SW) and Wyner-Ziv [0] (WZ) theorems. Let us consider two binary correlated sources X and Y. If the two coders communicate, it is well known from Shannon's theory that the minimum lossless rate for X and Y is given by the joint entropy $H(X,Y)$. Slepian and Wolf have established in 1973 that this lossless compression rate bound can be approached with a vanishing error probability for long sequences, even if the two sources are coded separately, provided that they are decoded jointly and that their correlation is known to both the encoder and the decoder.

In 1976, Wyner and Ziv considered the problem of coding of two correlated sources X and Y, with respect to a fidelity criterion. They have established the rate-distortion function $R*_{X|Y}(D)$ for the case where the side information Y is perfectly known to the decoder only. For a given target distortion D, $R*_{X|Y}(D)$ in general verifies $R_{X|Y}(D) \leq R*_{X|Y}(D) \leq R_X(D)$, where $R_{X|Y}(D)$ is the rate required to encode X if Y is available to both the encoder and the decoder, and R_X is the minimal rate for encoding X without SI. These results give achievable rate bounds, however the design of codes and practical solutions for compression and communication applications remain a widely open issue.

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