LAAS

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LABORATOIRE D'ANALYSE

ET D'ARCHITECTURE DES SYSTÈMES

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I. Global Scientific Project

1. Context and Challenges

One can anticipate changes and evolutions in the scientific and economical context in the next four years that the lab should be ready to meet. Their impacts on the evolution of our scientific topics, on our organization have to be prepared.

At a global level, there is a strong development of research reaching at smaller scales in the nanoworld. This triggers an unprecedented convergence between Information Sciences and Technologies and Biology, that is already present but that will certainly shift gears, and foster new research directions. Another global orientation is toward sustainable development and environmental concerns, including for example water and energy (re)sources and management. A third trend is the continual development of IST towards faster computing, more hardware and software integration, and extension of fast networking.

SWOT Analysis

Based on the above observations, and on the local, regional, national and international context, we have conducted a SWOT analysis that enabled us to identify a general scientific roadmap at the lab level and at the individual group level, and to decide for concrete actions.

Strengths

LAAS is very well positioned with respect to the major scientific evolutions. Its current scientific activities enable it to be prepared – if the adequate measures are taken – to meet the scientific challenges of the next decade, on the three main topics identified above.

Thanks to our success at the State-Region Project Contract with the project ADREAM (see the ADREAM section), we have a major instrument for implementing a scientific policy in the domains of cyber physical systems, ambient intelligence and photovoltaic power management.

The high quality level of equipment (e.g., from the BTR plan and other investments) and of human resources present at LAAS prepares us to quickly address new open issues.

The interdisciplinary character of LAAS and its strong relationships with academic research in different domains (chemistry, biology, …) prepares us to address new topics on the frontiers of existing disciplines.

Strong links with education and training (see of document "Report", annex 1) enable to disseminate knowledge and to motivate students for research.

LAAS mutualization policy and efforts towards enables to induce internal cooperation and explore new scientific directions.

Weaknesses

Mainly due to the financing model based on calls for proposals (instead for example of longer term financing based on programs), the researchers are close to saturation, spending much time answering to calls (or evaluating proposals).

Understaffing in the technical services results in very high solicitation of the technical staff, inducing.

Understaffing in administrative services implies hiring personnel on short-term contracts with an important turnover and loss of competence.

Opportunities

The foundation of the University of Toulouse federating its universities and engineering schools should enable a better scientific policy and a better capacity for hiring high-level professors.

IST and engineering is very strong in the region. University Paul Sabatier has organized its research in large clusters or domains, one of which is Mathematics and Sciences and Technologies of Information and Engineering, with a large Institute of Mathematics, three big labs in IST (IRIT, LAAS, LAPLACE) and several others in engineering. This will enable to address jointly complementary topics (cross-fertilization), and common issues (critical mass). One of the topics under consideration is ambient intelligence. Another – already exploited opportunity is the presence of ONERA – with which LAAS has signed an agreement in 2007 on a joint program on Aeroterrestrial Robotics and Autonomous Space systems, with collaboration with CNES.

Extension and strengthening of some topics due to the integration of people and teams from the LOSE and LATTIS labs.

Nanoinnov initiative and projects, the Ambient Intelligence initiative at CNRS are national orientations on novel areas of prime interest to the labs' topics.

Current and future implementation of new equipment and platforms (ITAV, Aerospace Campus) will widen and reinforce the regional capacities.

In terms of relationships with industry: strong ties with Industry (regional and national), good European and international visibility.

At the European level, LAAS topics are well represented in FP7 and also in the Competitiveness and Innovation Framework Programme (CIP).

Threats
The call for proposals and project-oriented general policy tends to require a reporting on the projects taking into account full costs and ignoring the necessity to mutualize within a research lab for defining and supporting a common scientific policy.

Difficulties for recruiting personnel according to needs (docs, postdoc, technical and administrative staff) are emphasized by heavy procedures, inappropriate regulations, and inadequate salaries.

2. Major scientific orientations

The lab has collectively prepared its scientific project, within each group and within each domain. The result of this work, focused on the groups and the domains is described in the second part of this document in each group and domain section. But we also have identified two **transversal scientific axes** that correspond to major scientific challenges, for which the lab has sufficient critical mass across the groups, and in which our involvement could have a significant impact. These axes will shape the new LAAS in the next decade and are developed next. This project was presented to our industrial partners of the Affiliate Club and was met with a very high interest.

1. INTERACTING WITH THE LIVING

The Laboratory's activity in connection with life sciences has been increasing sharply for several years. Initiated as soon as the beginning of the 80s through sensors developments, it has seen significant diversification whether it comes to the nature of the devices developed or the scientific and applicative fields addressed. It is supported by strong disciplinary openings and has required considerable technological evolution. It is probably not necessary to dwell here upon the societal and economic stakes which have produced and motivated such thematic evolution: public health and environment are at the core motivations and form a powerful drive. Moreover, as a main driving force, this domain provides an exciting scientific field of investigation and innovation in a cross-disciplinary and collaborative context.

The fundamental issue behind this domain remains to imagine, to design and to realize the tools which will enable to probe, to manipulate and to exploit biological matter at relevant scales: macromolecules, organelles, cells, tissues … and at performance levels that conventional approaches could not cover.

Nature uses highly sophisticated processes (for example selection, self-organization, and self-assembly) to provide an enormous range of "bio"-materials that ultimately form cells, tissues and organs. These materials exhibit remarkable memory, replication, self-healing and self-repair capacity. They also make use of quite diverse and particularly complex structural as well as functional shapes and architectures. Regardless whether for fundamental exploration, diagnostic or therapeutic purposes, such features suggests multi-shape but prioritized strategies, coupling various, complementary and converging approaches tending to analyze or exploit living matter through its structures, its functions and the fundamental interactions shown.

The knowledge and know-how acquired during these last four years confer the laboratory a thematic coverage available only in very few French laboratories: biosensors, nanobiosystems, micro and nanofluidics, are but a few of such elements and form a relevant working base for addressing the great challenges to come.

How will micro and nanotechnologies contribute to the diagnosis issue? Is there a way to show breakthroughs in the understanding of the mechanisms of living organisms?
Is it possible to draw inspiration from living organisms to design tomorrow technological and conceptual approaches?
What conceptual and technological breakthroughs?
What functional integration objectives?
What scientific and applicative challenges?
What cross-disciplinarity management?
These are hence, in this context, the fundamental issues feeding our prospective reflection.

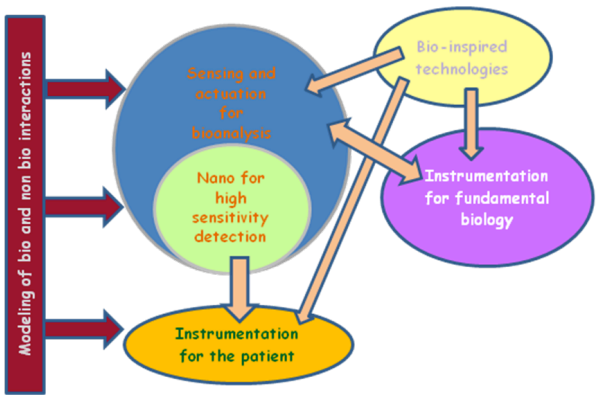


Figure 1. Schematic of the orientations for the "interacting with the living" axis

- **The Diagnosis Issue**

The first and primordial objective is related to diagnosis and drug discovery issues. The guideline is clearly to contribute to the development of tomorrow's technological, conceptual and software tools in order to provide and deploy powerful analysis solutions (lab-on-chip). To the detection conventional requirements: sensitivity, selectivity, specificity, reliability, security … are added

requirements in terms of functionalities: concentration, purification, separation, culture … Thus the topic implies the evolution towards more complex, more integrated, more intelligent systems but also induces to explore quite innovative aspects in connection with very low dimensionality effects, or disciplinary sectors outside our community. In that way, the scientific roadmap is twofold. The detection issue will be addressed on the one hand by the development of highly sensitive and label-free nanosensors: nanoFET, nanowires approaches will be privileged. On the other hand, new types of detection will be explored: RF detection and optical detection will be the priority. One driving idea is to measure and to model the eventual electromagnetic field generated by biological systems. Miniaturized passive and wireless sensors will be developed for the experimental exploration of such activities and for the derivation of the electromagnetic modeling of biological systems. The inverse electromagnetic problem will also be addressed: can we relate the characteristics of the electromagnetic field generated by biological systems to their biological activity? Can we derive the state of a cell from the passive, wireless and in vivo measurement of its electromagnetic activity?
The lab on chip domain will be explored through a multifunctional approach. While this domain was primarily addressing molecular biology it is now progressively moving to cellular biology. As a consequence, the effort will be put preferentially on separation or sorting aspects (hydrodynamic, magnetic, dielectrophoretic) and on the way to couple them efficiently.

Beyond the "bare" biological demand, the human dimension appears gradually, biology turning into health, test turning into diagnosis possibly prognosis, lab on chip turning into "Instrumentation for the Patient". Data transfer, processing, management and interpretation elements are becoming primordial. New techniques for bio matter analysis such as biochips are rapidly opening new area for disease treatment especially for the development of target therapies. By coupling results of biochip analysis (for instance those of tumor cells biochips targeting presence of Her2 receptors, proteomic dosage) with classical medical analysis and medical doctors' expertise, it should be possible to generate a personalized treatment. Nevertheless among the huge quantity of information provided by biochip analysis (from 1500 for a typical protein biochip analysis to 50 000 for a gene profile) and the imprecision of clinical information (such as cancer grade for example) there is a real need of an efficient methodology for at least an appropriate data pretreatment, or better, for the selection of the most pertinent information (note that in the precise case of cancer diagnosis maybe only very few descriptors will make the difference between the sub-types of cancer and so will influence the treatment given to the patient). A pure data analysis alone will not be able to model the complex links patient/treatment/disease outcome and predict the efficiency of a potential treatment. So, we propose to develop in parallel a way to introduce expert/medical doctor knowledge with the information given by a data classifier (for example by mapping Bayesian networks / inductive logic to this expert knowledge).

- **Fundamental Biology Issue**

During the past ten years, considerable efforts have been devoted to the development of new technologies for high throughput analysis in biology. The fields of genomics of proteomics, which were ushered in owing to DNA/protein bio-chips, have significantly increased our knowledge of biological systems, and in turn gave birth to systems biology, which aims at systematically studying complex interactions in living organisms. It becomes increasingly clear that our understanding of living systems cannot be limited to the level of genomes or proteomes, and new bio-systems for high throughput analysis at the cellular level (cellomics) and at the epigenomic level (Epigenomics) have been implemented, which both shed new light on molecular transactions in vivo. Taking advantage of successes obtained in the micro-nanopatterning of biological surfaces applicable to a wide field of biological experiments, LAAS intends to carry on its efforts and to design integrated systems for biomolecular and cellular analysis, and to propose cutting-edge innovative technologies that provide new biologically relevant information.
Alongside with these technological improvements, the field of live cell imaging has considerably grown in the last decade driven by the need for fast, robust and highly-resolutive imaging techniques. LAAS has recently gained competencies in fluorescence imaging as well as atomic force microscopy. Micro and nanotechnologies indeed enable the fabrication of fluidic components or microscopy probes that improve the control of experimental conditions, and the resolution of imaging devices, which together bring new insights on molecular processes in live specimens.

- **Bio-inspired technologies**

Seeking to use biomolecular unique properties of molecular recognition and self-assembly properties with the objective of creating novel structures, functions and devices for both biological or non biological applications is attracting a growing interest. Therefore, the associated emerging field of Bio-inspired materials is now opening new routes for the development of hierarchical architectures, highly

hybrid nano-systems (inorganic/organic/bio) conceptually inspired by Nature.
In this frame, DNA appears as a leading structural material, thus diverted from its original role of carrier of the genetic information. Initiated by Seeman (branched DNA, DNA tiles as elementary building blocks) and, later on, by Rothemund (DNA origami), DNA-based nanotechnologies have reached a level of maturity enabling: (i) reliable "bottom-up" nanoconstruction of a wide range of possible shapes, (ii) DNA arrays to template the assembly of other functional molecules, (iii) vectorization and molecular recognition through DNA Aptamers.
Because of the underlying technological revolution accompanying this research axis, notably in its confrontation with other traditional micro and nanomaterials (integration issues), LAAS-CNRS has begun a strategic reflection on its potential role into this multi-disciplinary field. In the next years, the LAAS-CNRS wishes to develop bio-inspired technologies, particularly on the side of their integration pointing towards functional micro and nanodevices. Two applications are currently being envisaged: DNA-based nanoenergetic materials and aptamers for micro and nanofluidic systems.

- **Modeling interactions of and with living organisms**

Nowadays, computational techniques are increasingly used in structural biology to model bio-molecular interactions in order to analyze the relationship between protein structure and function, and, in the long run, to help understanding the molecular machinery of the cell. Given the current progress of nanoscience, one can expect in the near future a similar increase of the demand on simulation techniques to help for the construction of new functional nanomaterials, with applications in nanotechnology and medicine.
Both domains require high-performance, atomic-resolution simulation tools able to tackle the important challenge of macromolecular flexibility. In structural biology, proteins are flexible macromolecules, often changing their conformation when interacting with other molecules. However, modeling structural changes during the docking process, as well as designing fast but yet accurate virtual screening tools for computer-aided drug discovery or protein engineering are today bottlenecks for state of the art techniques. In nanoscience, the in-silico design of molecules with high affinity for binding on a solid inorganic surface, or the simulation of molecular self-assembling to yield nanostructured materials, are yet largely unexplored domains.
Future progress in these domains asks for the development of multi-disciplinary, cutting-edge, computational techniques. Building on the complementary expertise from MINAS and RIA, routed in well recognized results, we aim to get new insights on these challenging problems with innovative multi-scale approaches combining the algorithmic efficiency of techniques issued from robotics research with the accuracy of new physico-chemical models.

2. ADREAM

The ADREAM project (french acronym for "Dynamic Architectures for Networks of Mobile Embedded Systems") finds its roots in the successful proposal we have made to the State-Region Project Contract (CPER 2007-2013) in 2006. Initially it was oriented towards the financing of a **new building** and **new equipment** related to extending the design, and networking platforms and setting up an embedded systems platform. During the years 2007-2009, we have worked on the scientific foundations of this project and evolved it considerably. The building that has been designed and that will be constructed during 2010 is now an **intelligent building** and has a photovoltaic facade and roof. It will also host research teams on photovoltaic energy management which will develop new energy conversion systems. In terms of the scientific objectives, the project is focused on the topics of "**Ambient Cyber Physical Systems**".

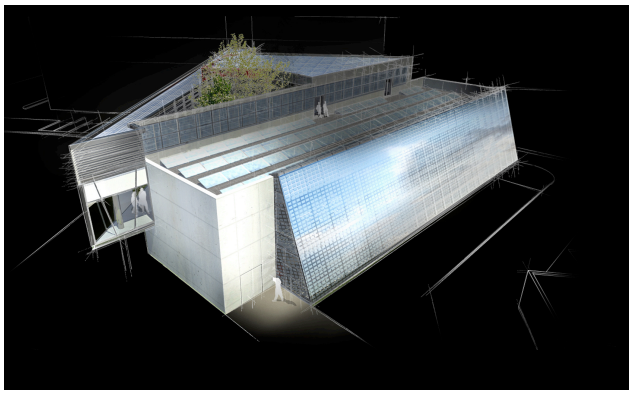


Figure 2. The new ADREAM building (1200 m^2) with photovoltaic facade and roof

The domains of Integrated Systems, Robotics and Networks have known considerable progress these past few years. A new trend has also been identified, mainly in the United States, fostered by NSF, and called "Cyber Physical Systems" that puts the emphasis on considering jointly the constraints of hardware and software and operating conditions. This emerging theme pertains to systems in strong interaction with their environment and subject to its constraints and dynamics. These systems are heterogeneous, possibly embedded, include sensing and actuation, and can be mobile. They have to meet operational constraints in terms of time, energy, etc.

and be adaptive and resilient. We add to this problematic that they can be networked in a reconfigurable fashion (hence the term "ambient").

Based on our strengths in these domains, we have decided to explicitly identify a transversal research axis in this area, called **ADREAM (**Dynamic Architectures for Networks of Mobile Embedded Systems).

In this context, we consider the problems of modeling, design, experimentation and performance evaluation of such systems, all of which require to develop appropriate methods and tools. The global system's components (sensing, actuation, decision-making, communication, energy management) have to be considered jointly so that their mutual constraints are taken into account in a comprehensive approach. Research will be at three levels:

- Global design methodology, including :
  - Multiscale modeling and validation
  - interoperability,
  - adaptation to energy variation,
- System operation:
  - Sensing, perception, interpretation,
  - Control
  - Decision making
  - Quality of service and dependability
  - Energy management,
- Integration and Experimentation
  - Sensors and actuators, from the micro scale (MEMS),
  - Wireless communication systems, smart antennas,
  - Distribution and networking of cooperating sensors,
  - Autonomous Robots and mobile communicating devices.

A requirement will be to consider at all times the fact that all the systems are interleaved and influence each other, and that their operating modes have to cope with degradation of communication and energy sources.

3. Integration of the LOSE and the LATTIS

The LOSE (Laboratoire d'Optoélectronique pour les Systèmes Embarqués of INPT) and LATTIS (Laboratoire Toulousain de Technologie et d'Ingénierie des Systèmes of INSA) are two laboratories working on topics close to those of LAAS and IRIT. The decision has been taken by the two institutions INPT and INSA and by the laboratories directions to join them with the two larger labs.

Scientific and organizational discussions have taken place since 2007 with LOSE and in 2009 with LATTIS. This integration would enable to open new directions and to strengthen existing topics at LAAS.

LOSE (6 professors and assistant professors) works on the design of optoelectronics sensors as well as their micro-electronic circuits for generating and acquiring optical signals. They investigate the physical limits of laser sensors in terms of both theory and methodology of measurement, as well as the information-theoretical limits of algorithms to process data. These issues are not addressed today at LAAS, even if there is a clear proximity to the Photonics group (PHOTO). LOSE members will work with PHOTO on joint projects in 2010. However we anticipate the integration of LOSE as an identified group, OSE (Optoelectronics for Embedded Systems) at least for the first part of the next 4-years period before considering a possible fusion with PHOTO. The scientific project of this group is detailed in this document.

LATTIS situation is different. The addressed topics fall in various groups at LAAS and the integration plan is currently as follows:

- Two persons working on artificial muscles in robotics will join the GEPETTO group
- One person working on safety issues will join the TSF group
- Two persons working on systems engineering will join the ISI group
- One person, already affiliated to LAAS working on sensor networks will join the N2IS group
- Three persons working on electromagnetic compatibility will eventually joint the MOST group, after more scientific discussions.
- Six person working on Nonlinear Dynamics and Chaos will form a new group at LAAS called DYNOC within the MOCOSY Domain. The scientific project of this group is detailed in this document. The DYNOC group will be located at the INSA on campus. However the group will be fully integrated in the LAAS organization and activities.

4. Process for renewing LAAS direction

In 2010 we shall start the procedure for renewing the direction for the next four years. A committee for the lab council will be formed to manage the process: calls for candidates, organization of hearings and general assemblies of the lab, vote at the lab level and at the council level. The new direction might propose some evolutions in the organization of the lab.

5. Industrial Relationships

Industrial partnership will remain a high priority of the lab. In addition to our usual actions, i.e., direct contracts, joint labs, collaborative projects, Carnot label, we want to put some focus in the next period stimulating the creation of **startups**. Early 2010 we will start a program with the help of a consultant with experience in entrepreneurship. The program includes a series of workshops oriented towards the lab personnel for identification of possible markets for innovations resulting from research conducted at LAAS, and methodology for setting up startups.

II. RESEARCH GROUPS SCIENTIFIC PROJECTS

Research domain
MIcro and NAno Systems – MINAS –

As it will clearly appear through the research Groups projects and orientations, the key objectives that will be addressed by the MINAS area are strongly motivated by the emerging and challenging fields of Distributed Systems and Internet of Things, and by the convergence of Nano and Bio paradigms.

These perspectives impose to strengthen our long term investing in multifunctional integration but also involve a progressive and inevitable shift of activities towards cross-disciplinary topics. This will be accompanied with significant technological and conceptual evolutions. In that context, MINAS will emphasize multiscale and multidisciplinary approaches. Nanosensors, nanoscale microwave, nanophotonics, nanosources, nanobiomachines, nanofluidics will be a few of the key points driving the technological effort. Reconfigurable systems, sensor networks, integrated functional architecture, robustness and reliability, advanced simulation and design will constitute some of the main issues at the system level.

The dynamics of this evolution will be fully anchored in the general dynamics of the laboratory. Interactions with other research areas (SINC, MOCOSY, RIA) will increasingly exist and will reinforce a coherent perspective of autonomous and smart systems from device aspects to embedded systems aspects. The MINAS area is an actor of the ADREAM inner program and will carry out several collaborative projects together with the other areas in the frame of prestigious and challenging national programmes as NanoInnov or RTRA (Network on Thematic Advanced Research).

11 senior members from the LATTIS laboratory and from the OSE research team will join MINAS. They will permit to extend our skills at the system level particularly through integration aspects of optoelectronic systems and electromagnetic compatibility. They will also strengthen our activity in the application field of smart home systems.

In the domain of nano bio technology, MINAS has played an important role in the creation of ITAV (Institute of Advanced Technology for Life Sciences). This site will be a unique opportunity to build and reinforce cross-disciplinary skills and will constitute a privileged tool for incubating joint projects with biological or medical teams.

The MINAS strategy will be also to foster shared initiatives. The general strategy is depicted in the section “Interacting with the living”. However it is worth pointing out that, among all the collaborative topics, bio-inspired technologies have been identified as a promising issue that could be shared between several groups through various but complementary aspects and approaches: DNA and Aptamers, proteins and cells. This trend will be reinforced by the future equipping of an instrumental platform dedicated to biological and chemical matters.

Integration of Systems for Power Management – ISGE –

Context and Challenges

One of the big challenges that governments will have to face over the next decade is related to energy issues. Worldwide, most of the energy is consumed into transports and buildings, both residential and industrial, thus resulting in a significant increase of CO_2 emissions and in global warming. The majority of this energy is generated by non-renewable and non-environmentally friendly coal, fossil fuel and natural gas. To overcome such issues, the widespread of alternative energy sources in transportation and buildings is the solution that will require a major paradigm shift in the power industry:

- Transports will have to become more electrically driven thus demanding for new generations of power devices and converters.
- For a large penetration of renewable energies, it is more appropriate to move from a centralized generation approach to a distributed one.

Moreover, the advances in power electronics and microsystems technologies allow envisioning the drastic miniaturization of power generation and management systems that should enable the energy autonomy and then the large dissemination of wireless sensor networks. The main challenges are on the one hand, the development of efficient energy harvesting and scavenging approaches coupled to ultra low-power converters and on the other hand, the availability of integrated high-density storage devices.

These challenges can be divided in two important topics that will structure ISGE group research activity for its (2011-2014) project:

- Power systems and harsh environment
- Energy and distributed systems

Major research orientations and projects

Power systems and harsh environment

Heterogeneous power integration

New research: *Wide band-gap semiconductor devices*

As detailed into the (2005-2009) activity report, new architectures of silicon power devices were developed to improve their performance. Nevertheless, these improvements appear to be insufficient because of the increasing demand for electrical power: for instance, for hybrid and electric vehicles, high voltage devices (≥ 600V) exhibiting very low on-resistances, high switching frequencies and high temperature operation are required. Silicon devices are generally limited to a junction temperature operation in the range of 200ºC and have other characteristics that make them less than ideal for future power devices. The major breakthrough in power semiconductor devices is expected from the replacement of the silicon material by a wide band-gap semiconductor (Silicon Carbide –SiC–, Gallium Nitride –GaN– or diamond), which offers the possibility to overcome both the temperature and power management limitations of Si.

Recently, GaN became more and more popular not only for optoelectronic and RF applications but also for power applications. However, its application to power switching still requires further research work in the field of materials, process and device design. Much progress has been made in field-effect transistors using AlGaN/GaN heterojunctions for carrier confinement that, given the high electron mobility of these heterostructures, exhibit very low on-resistance. Unfortunately these devices are only normally-on devices. Normally-off devices are preferred for logic and power devices, since they ease the design of driving circuits.

The main objective of the current and future projects (MOreGaN, ToPoGaN) will be to propose and fabricate new architectures of lateral and vertical normally-off GaN unipolar devices (MOSFETs and HEMTs essentially) with high-quality GaN epitaxial layers and high-quality 'dielectric/GaN' interfaces (for the MOSFETs), i.e. devices exhibiting high blocking voltages and very low specific on-resistances [ACTN306]. To achieve this goal, several key process steps have to be studied and strongly improved: epitaxial growth, dielectric deposition, passivation, implantation, annealing, etching and metallization. This work will be mainly carried out in cooperation with CHREA, LAPLACE, LETI and Freescale.

The diamond is a semiconductor material with exceptional properties, which makes it an ideal candidate for power electronic devices. For example, breakdown electric field (10 MV/cm), thermal conductivity (20W.cm-1.K-1), hole mobility (1800 cm².V-1.s-1), electron mobility (2200 cm².V-1.s-1) are the most significant properties that are relevant for power electronic devices. Recent progress in the synthesis of high-quality CVD diamond thick layers, compatible with the microelectronic technology, offers the possibility to achieve electronic devices with unprecedented properties. A first Schottky barrier diode with 1200 A/cm^2 current density at 5V forward bias was measured, proving the diamond potentialities for high-current active switches. However, to develop diamond-based electronic devices, the technological steps of diamond epitaxial growth, mesa etching, ohmic and Schottky contacts

fabrication still need further research studies. The first power electronic device we want to study and fabricate at LAAS is a high voltage (10 kV) and high temperature (500K) p-type Schottky barrier diode and Field effect Transistors. Such devices should allow developing very high power density converters.

Research in continuity: *3D heterogeneous integration*

Concerning the integrated passive L and C components for power applications (future micro DC-DC converters), one major integration challenge still remaining is the development of dielectric and magnetic materials adapted to the application objectives.

For magnetic materials, the electrochemical deposition of NiFe and NiCoFe is now well mastered. Efforts should be focused on reducing the conductive microinductor losses related to the copper conductor high resistance value (about 1Ω DC). Increasing the conductor section seems a natural way but it also increases the device size. To avoid this drawback, the global topology of the microinductor will be revised.

For high-k dielectric materials, the ANR project Camino helped understanding the deposition problems (3D conformal deposition, material phase and composition control). The electrical characterizations were adapted to the particular case of high-k materials. In the near future, we are planning to develop a deposition method in LAAS clean room, such as MOCVD or ALD for perovskite type material showing very high permittivity (> 200): $SrTiO_3$, $BaSrTiO_3$.

To further miniaturize power systems, the integration of several passive components (L and C) on the same substrate has to be realized as well as within an active circuit (see self-power supply below). Not only technological issues to obtain compatible fabrication processes have to be solved but also challenges related to power applications: namely, connections with minimum losses to carry several amperes, high voltage isolation between active and passive components and adapted thermal management.

Considering the realization of self-switching mode devices dedicated to static converters for renewable energies applications, two circuit topologies have been proposed. The basic building blocks were separately validated (see activity report). To integrate the complete self-power supply, a new technological process compatible with the IGBT process and 3D capacitors realization has just been optimized and will be implemented shortly. In a long term, we plan to integrate the complete switching cell to achieve current bidirectional converters for renewable energies such as wind turbines or photovoltaic cells.

Concerning the development of bidirectional IGBT structures (MOBIDIC ANR project), the realization of the bidirectional IGBT using the Si/Si wafer bonding technique is the most challenging part of the project. The major difficulties to overcome concern mainly the quality of the wafer bonding interface and the wafer thinning. The next objective will be the monolithic integration of the IGBT gate driver power supply elements, which requires the integration of 3D silicon capacitors. Therefore, it will pave the way towards 3D heterogeneous power integration for the realization of new switching functions.

Furthermore, for AC domestic power applications and more precisely for “intelligent buildings”, in the long term, implementing a communicating interface integrated with or close to the Bi-IGBT would make it an intelligent communicating switch allowing a better energy management within the buildings.

Robustness and reliability: protection

New research topics:

“ESD Protection of emerging technologies” — Disseminating new high-tech systems based on micro or nano technologies requires a high robustness to ElectroStatic Discharge (ESD). Protection measures are needed from the standalone device to the full system. While technologies scale down and introduce new process steps to improve or to build innovative applications, it is often at the expense of a lowered ESD robustness. An alternative protection solution is to use new materials to build, above the integrated circuit (IC) or microsystem, passive protections such as varistor devices that are independent of the technology to be protected and scalable both in current and voltage through layout. The pioneering work on Zinc Oxide (ZnO) carried out within LISPA joint lab with Freescale in cooperation with Laboratoire de Chimie et de Coordination (LCC) demonstrated that ZnO nanoparticles plus identified additives can be used as a starting material to prepare varistor devices through a relatively low-temperature process compared to the state-of-the-art preparation. A low-temperature process is indeed key for integrating such device at the end of an advance technological process (above IC) and more generally to be compatible with a broad range of state-of-the-art microsystem process. The prospective work focuses on, but is not limited to, ZnO as the starting material. Two main goals are identified: on the one hand, demonstrate a low-temperature (<300°C) integration process and on the second hand, thoroughly study and understand the relationship of the processed material and the physical origin of its electrical characteristic, especially at extreme current density level required for ESD protection. This new understanding will allow refining the composition of the material and its related integration process toward new, low cost, integrated ESD protection devices.

"MEMS ESD protection" — MEMS devices are now emerging for a large variety of applications (medical, RF, automotive, aeronautics, security…). However, their ESD sensitivity constitutes a real reliability issue. Due to their mechanical parts with small air gaps, they are very sensitive to ESD stress during packaging, assembly or even within some applications. Many types of MEMS devices are developed in LAAS clean room facility for various applications. This is a great opportunity to develop co-design approaches to improve their reliability and ESD robustness and to experimentally validate them. The stressed devices generally exhibit two kinds of degradation: catastrophic ones resulting in metallization blowing or dielectric breakdown; latent defects susceptible to reduce the MEMS lifetime. The prospective work is split in several topics:

- MEMS behavior analysis during an ESD stress
- Dedicated ESD characterization methods
- MEMS design optimization to improve ESD robustness
- Dedicated ESD protection implemented on the MEMS chip or using dedicated SIP ESD protection (ex: using ZnO-based protection devices)

"Radiation hardening and protection of power devices" — Nowadays, the power electronics needs are increasing due to the strong demand of applications based on electrical energy (transport-by-wire, embedded systems). This increase requires a better energy management and an improved reliability of power systems. Space and aeronautics environments do not escape from this tendency with an additional constraint related to the Natural Radiative Environment (NRE). Power management systems use conventional power devices such as MOS and IGBTs that are particularly sensitive to the NRE particles. Two types of failure are observed on these devices: the SEB mechanism (Single Event Burnout) associated with the turn-on of bipolar or thyristor structures and the SEGR (Single Event Gate Rupture) that can lead to the gate oxide breakdown. The motivation of this new research topic is to design and validate protection solutions against ion effect on these power devices and their associated modules, thanks to the analysis and understanding of the physical and electric mechanisms involved during these radiative events. This study will be extended, on the one hand, to the advance generation of silicon power devices (Superjunction MOSFETs, trench IGBTs,…) and, on the other hand, to wide-band gap power devices (SiC, GaN).

Research in continuity: *ESD protection strategies and modeling*

We have been working for many years on the optimization of ESD protection devices integrated with the IC to be protected. To broaden the spectrum of this research activity and tackle the challenges of an improved ESD robustness of embedded systems, we will extend our approach to both dedicated ESD protections and to a global system level ESD protection strategy. This defines three main research activities:

- Integrated protections for advanced CMOS technologies (65nm, 45nm and 32nm nodes), in close cooperation with STMicroelectronics in Grenoble (France) and IMEC (Belgium).

- Mobile electronic devices are submitted to harsh environments and human repetitive contacts. A new requirement emerges for protection elements that sustain very high voltage level (15kV) and repetitive (>1000) discharges. Only dedicated protection devices can fulfill such requirement. They are based on diodes whose reliability and robustness need to be improved through a thorough understanding of degradation and failure mechanisms. This work will be mainly carried out with STMicroelectronics in Tours (France).

- System level ESD has gained a growing importance over the 2 last years. The research objectives are the development of behavioral models for the prediction of the impact of ESD events at the level of a full system, both powered and not powered and the development of a set of precise characterization benches and testing methodologies for experimental validation. Up to now, no standards exist to quantify system level ESD and we will interfere with the ESD standard committees to propose EMC/ESD co-measurements. This activity is supported within the European PROSE – CATRENE project and in collaboration with On Semiconductor in Toulouse (France) and Belgium.

Robustness and reliability: modeling

New research topic: *On-chip predictive reliability management*

To optimize the design of a power module with regard to its reliability improvement, it is of primary interest to first get an in-depth knowledge of the physical phenomena (mechanical stress and temperature) that could lead to a failure. Furthermore, additional real-time information about the mechanical state of the chip would be essential to predict the device degradation and then avoid its fatal failure. Such information can be extracted from the electrical characteristics, which are dependent on the mechanical stress but also drastically dependent on the temperature. To extract the information of the mechanical stress from the electrical characteristics, it is advantageous to dissociate temperature and mechanical effects [ACTI1515].

The innovative proposed concept consists in the realization of a silicon demonstrator allowing the

follow-up of the remnant mechanical state of the power device assembly in its functional environment with the objective of a predictive reliability management of the power module. This ANR InterCarnot project, ReMaPoDe (Reliability Management of Power electronic Devices), will be carried out in cooperation with IMS (Bordeaux) and INRETS LTN.

The main challenges of the project are the identification of the electrical parameters that are sensitive to the mechanical stress, understanding the involved physical mechanisms and the design of an integrated mechanical state indicator test structure as final demonstrator.

Research in continuity: *Electrothermal modeling*

The strong miniaturization of embedded power systems in applications such as the aeronautics one pushes the power components towards the limits of their safe operation area. In addition, as more and more safety-related functions (cars, aeronautics…) are controlled by these components, end-users ask for a zero-default requirement. In this context, the study of the reliability of the power components must take into account various interactions such as the electrical and thermal coupling. The main challenge of electrothermal modeling lies in the great difference in scale (of both time and dimension) between the two phenomena. Moreover, it does not exist a single solution but a multitude of ways to consider this coupling depending on the considered application. The proposed approach is based on a distributed electrothermal modeling to provide an efficient and predictive tool of assistance to the designers of the new generations of integrated power components. This work will be carried out in close cooperation with industrial partners and in particular, within ELIAS European project in tight collaboration with Epsilon company and within the framework of two ANR projects, MOS i-StARS and Mhygale with Valeo and Freescale.

A more academic action will target the automatic heat capacitances extraction in order to build thermal compact models for complex geometry cases in dynamic mode operation. Finally, the analytical models for the power devices, such as the IGBT and the diodes, will be simplified and coded in VHDL-AMS to ease their integration in the electrothermal modeling.

Energy and distributed systems

Renewable energies

Our ambition is to contribute to energy savings and reduced greenhouse gases emissions by tackling the challenges of the integration of renewable energies, in particular the photovoltaic one, in buildings.

Based on our past experience of conversion architectures for embedded systems and renewable energy, the integration of global technology solutions, saving energy and using renewable energy while ensuring user comfort, safety and health of users will be privileged for energy management in buildings. This is multidisciplinary research activity focusing on the development of innovative technical solutions, easy to implement and maintain, and including reliability aspects, issues of acceptability and adaptation to customers and behaviors, cost analysis. Moreover, these technological solutions aimed at radically reducing the energy consumption in new and existing facilities, will have to comply with future regulations. Although in continuation with our previous work, this activity is tackling the challenge of the validation on a real scale application with the support of the future ADREAM platform (100kWc). To fulfill these requirements, we propose to focus our research activity on the following topics:

- Smart Distributed Architectures: as a continuation of the work presented in the activity report, in areas such as renewable energy or embedded systems, the work will focus on the development of innovative multi-phase, low voltage-high current architectures, with improved efficiency and compactness through the increase in operation frequency and integration, as well as improved reliability and lifetime. These distributed architectures should be able to communicate with each other and to an outside observer, to allow reconfiguration on demand. For the specific area of embedded systems, new digital control laws will be proposed to push the limits of the operation frequency of the converters without degrading their performance and reliability [ACTI1371]. This work, will be carried out in collaboration with the MAC Group of LAAS-CNRS as well as the University Rovira i Virgili of Tarragona (Spain).

- Converter Integration: the goal is to meet the requirements of the compactness versus performance trade-off. Based on the experience gained through the ANR ATOS project on the development of converters dedicated to the management of energy from advance photovoltaic cells, the challenge is the miniaturization or the integration of the conversion chain. This activity will benefit from the ISGE group experience in the field of integration of power components and passive elements as well as the EMC issues in integrated structures.

- Coupling of energy sources: we intend to strengthen our previous activities on the issues of electrochemical storage. Two types of batteries will be studied: lead and lithium. In each case, we will continue the studies on Battery Management Systems (BMS) and the associated models. The storage

element lifetime versus the number of charge/discharge cycles will be one of the main criteria, together with the final system compactness, its low consumption and its integration to the chassis. For experimental validation, studies on isolated systems implemented in the future ADREAM building will allow testing the developed solutions using consumer profiles from real life cycles. These studies will be carried out in cooperation with INES and CEA LITEN [ACTI1144].

Autonomous systems

Applications of Wireless Sensors Networks (WSN) are blossoming and, whatever the application, the issue of the autonomy in energy is crucial. For a lot of systems, chemical storage, i.e. batteries, is a possibility. In this case, insuring a sufficient autonomy requires high yield, low power, energy conversion and signal processing circuits. Nevertheless, there are many classes of applications for which batteries, rechargeable or not, are not practicable. The limitations are linked to their use under extreme temperatures (high or low), which raise safety issues (risks of fire or explosion).

In that situation, capture of energy from the environment is mandatory. It is also necessary to perform transient storage of that energy, and given its limited availability, to devise an efficient global management of the conversion and distribution of the energy towards the signal processing circuits of the WSN node.

In that context, we are planning to develop studies in the field of energy management applied to WSNs implemented in aeronautics or even space applications. This activity was recently started in ISGE group in cooperation with N2IS group and AIRBUS within AUTOSENS Project funded by FRAE [ACTI1374] [ACTN349]. Considering aeronautics issues, such a WSN would have to perform Structural Health Management (SHM) of critical components of an aircraft. The expected benefits are the decrease in inspection costs, the optimization of margins in mechanical design, and consequently, the reduction of aircraft weight, fuel consumption and emissions of greenhouse gases.

For energy capture, two principles may be considered, called energy harvesting (continuous source) and energy scavenging (intermittent source). However, availability of energy is in both cases limited, and multiple energy sources should be considered since it may occur that a single category would not be enough to power a node during all phases of a flight. Time shifts in the availability of environmental energy together with intrinsic different time constants of the transducers and the by-nature synergy between scavenging and harvesting may praise for such a multi-source configuration.

Our work will aim at the design of integrated systems for (low-power) energy management, a battery-less system being the ultimate challenge. They will combine multi-sources of energy (i.e. photovoltaic cells, Peltier or piezoelectric modules, and storage elements (i.e. supercapacitors). For these functions, the maximization of the energy transfer will be the privileged parameter. Then, we will devise high yield, ultra-low power conversion components to power the signal processing circuits of the node. For this step, the energetic yield will be the parameter of interest. More important, we will develop circuits and a simulation tool to achieve efficient cross-functional (capture, storage and usage for sensing and communication) energy management.

To insure an efficient storage of the harvested energy, the integration of the storage device is considered as close as possible to the harvesting device. Supercapacitors are a logical choice when it comes to extreme temperature ranges. Since 2007, a new activity on the integration of micro-supercapacitors on silicon has thus started in the AUTOSENS project with the collaboration of CIRIMAT. The first results are promising: a micro-supercapacitor was realized using a new inkjet printing technology process. Recent results show a state-of-the-art supercapacitor with 5 mF/cm² of capacitance with a voltage window of 2.5V. In the next years, we will focus on higher energy density storage microdevices with the development of various microtechnologies (screen printing, inkjet printing of nanoporous carbon materials) and electrodes nanostructuration (Si or SiC substrate). An exchange program (Partner University Fund) with the Drexel University (USA) will start in September 2009. Through the tight collaboration with Prof. Yury Gogotsi team, who develops nanostructured carbon-based materials, we expect a major scientific breakthrough concerning new electrochemical phenomena at micro and nano scales. The final goal is a fully integrated system with the energy harvester, the storage and the associated electronics.

Micro and Nanosystems for wireless communications – MINC –

Context and Challenges

In the context of recovery plan to get out the major worldwide economical crisis, it has been admitted that breakthrough in research and innovation will be an essential issue that is reflected by an increase of interdisciplinary research and an enhanced private public partnership to simulate the innovation and the technological transfer. The field of Information, Communication Sciences and Technologies (ICST) is recognized as being a corner stone that will stimulate significant added value at a system level for strategic industrial sectors as :

- Energy
- Transports
- Security and safety
- Telecommunications
- Health
- Environment

Europe is playing a leading role in this area for many years that has been reinforced during the 7th Framework program through the instrument of European Research Platform (ERP) that is covering the entire scientific and technological spectrum from material level to system and system of system level as depicted in Figure 1.

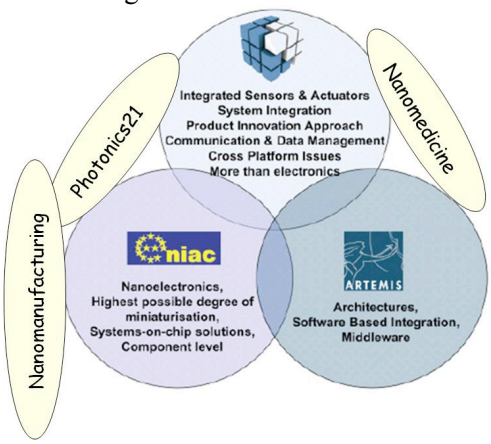


Figure 1 : Main European Research Platforms in the ICST domain

This has motivated the concept of **smart systems where the technology convergence, the progress at the frontier of science is enabling new class of systems featuring augmented capabilities** that will bring significant added value to the aforementioned industrial sectors.

Wireless communications are considered as an important building block in this context of **smart systems through the emerging field of Internet of Things (IoT)**. After a decade of intensive deployment of wireless communication applications, it appears that the allocated spectrum is for one hand overcrowded and vastly underutilized for another hand stimulating research to insure a better use of the entire electromagnetic spectrum in term of resources allocation (frequency bandwidth, energy consumption) that will play a significant role for the sustainable development of the society.

Our aim is to bring a contribution to the next generation of wireless systems referred to as **"Cyber Physical Wireless Systems (CPWS)" through developing research and innovation in the field of Electromagnetic energy engineering from material to system level.**

Our contribution will be organized into four flagships as listed below:

- Smart wireless components and circuits
- Green RF electronics
- Smart wireless sensors network
- Advanced simulation and modeling for complex wireless systems

Each of these flagships will involve both basic research to advance at the frontier of knowledge and more precisely emphasizing the multi-physic and multi-scale issues and public private partnership to accelerate the transfer from knowledge to innovation to support the competitiveness of French and European industries. In this context, we will bring a contribution to the "NanoInnov" initiative launched by the French government in 2009.

Major research orientations and projects

In this section, it will be given a more detailed description of the research activities that will be envisioned during the next period and that will be articulated around existing projects that are already running and for which there are commitments and new projects that are planned to be proposed to handle the flagships outlined. Special attention will be paid to develop public private partnership around projects featuring high potential and to international partnership to leverage our research activities.

Smart wireless components and circuits

This challenge will concern the exploration of different solutions to develop innovative devices and circuits featuring advanced capabilities. The research activity will address the following topics :

- Nanoscale microwave
- Ferroelectrics devices
- RF MEMS devices
- Innovative RF devices and sub-subsystems

"Nanoscale microwave" — Concerning the topic "nanoscale microwave", we intend to explore the potentialities exhibited by nanomaterials and nanostructures for high frequency applications up to THz range. Initial works have been done concerning

nano ink involving carbon nanotubes (CNT) or Fe_3O_4 nanoparticles. Figure 2 is depicting an example of such "nano ink" deposited with an ink jet printer.

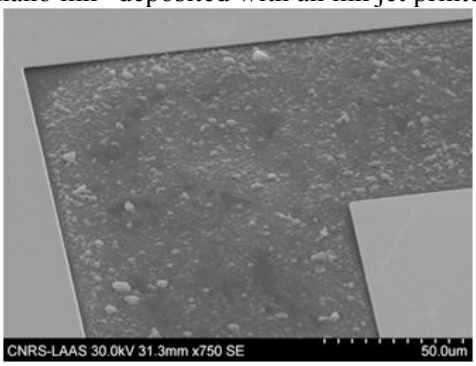


Figure 2 : Fe3O4 based nano ink deposited with ink jet printer

Other research will be conducted concerning the potentialities of Graphene materials to do either new RF electronics including reconfigurability or tenability. Figure 3 shows an example of a coplanar wave guide loaded with a grapheme sheet that has already demonstrated attractive capabilities for microwave switching.

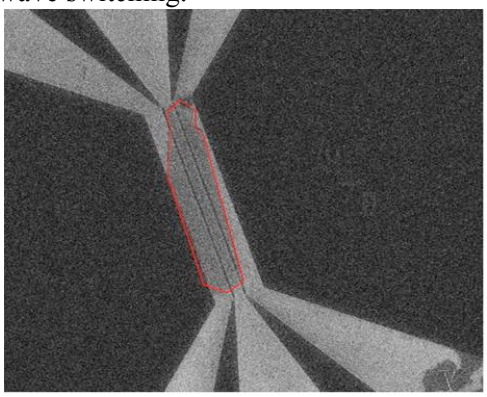


Figure 3 : Coplanar waveguide loaded with grapheme sheet

We also have demonstrated that crossed suspended carbon nanotube could translate to very interesting behavior in the RF frequency and based on preliminary results obtained on both CNT and Graphene sheet, we intend through collaboration described latter on in this section to develop a new RF electronic technology exploiting their fantastic capabilities and featuring on the same chip MEMS, sensing capabilities and analog circuits.

Another very interesting issue we plan to work with deals with the RF energy harvesting using nanotechnology and nanostructuration. Two main projects will be conducted. The first one deals with the exploration of the Giant Seebeck effect of CNT carpet induced by RF energy that we have to demonstrate experimentally. The second one deals with the exploration of the Ratchet effect to create microwave components either for energy harvesting of miniaturized demodulator. This effect consists to nanostructure an heterostructure and to illuminate it with an appropriate microwave signal.

"Ferroelectric devices" — This project has been initiated two years ago in collaboration with ICMCB laboratory in Bordeaux and deals with the exploration of the potentialities of BST thin films for reconfigurable microwave devices and circuits. From preliminary works, it will be investigated power handling, temperature evolution and BST based circuits will be designed and fabricated (impedance synthesizer, Phase shifter, tunable filter). Additional works will be done concerning the potentialities of LSMO that have been initiated and that have to be consolidated in the future. Finally, we are intending to initiate a partnership with CIRIMAT laboratory to investigate the potentialities of ferroelectric nanowires to create innovative RF components.

"RF MEMS devices" — This project has been initiated 15 years ago and the last period has seen a lot of progress concerning the technological process, the knowledge of physic of failure and the ability to have a component library to form more complicated reconfigurable components. For the next period, we expect to orientate our efforts to design and fabricate MEMS based sub-systems (i.e millimeterwave phase shifters, MEMS based Reflect arrays, tuner for smart amplifier) where it will be important to have robust model and stable process to be able to fabricate sub-systems featuring thousands of MEMS. In order to have a stable process, Physic of Failure research will be continued through material investigations with AFM/EFM method in order to better assess the dielectric charging and to propose solution to minimize or at least to model to be able to predict the life time of a MEMS based system. This will be done through a partnership with Laplace and LPCNO laboratories in Toulouse. It has to be emphasized that this activity will be completed with the development of on wafer packaging capabilities and by optimization concerning the power handling. This RF MEMS activity will be finalized during the next period through a project proposed at the "AESE pole de competitivité" in order to be able to propose a foundry service for aeronautic, space and defence applications. Concerning research activity, we will concentrate on:

- the miniaturization towards NEMS RF to form tunable millimeter wave and THZ resonator and antennas
- development of low actuation voltage RF MEMS using piezoelectric actuator and nanowire based actuator.

"Innovative RF devices and sub-systems" — This project will address innovative devices and sub-systems resulting from technology convergence. The first issue we will consist to merge RF MEMS with

BST based components in order to demonstrate the concept of microwave circuits featuring both coarse and fine tuning capabilities that could result in more flexibility for the future wireless architectures. This merging between MEMS and ferroelectrics material will also be used to develop miniaturized reconfigurable scatterers for wireless sensor identification. This concept will also be used to extend some works that have been initiated concerning reconfigurable metamaterial and reconfigurable circuits using Defect Ground Structure concept.
A third issue will be related to the demonstration of very sensitive RF MEMS/NEMS based power meter in order to introduce some testability at the analog level within the wireless architecture.
Finally, the last issue is aiming to develop new RF devices through the exploration of Substrate Integrated Wave Guide Technology (SIRW) to create microwave and millimeterwave components that will be conducted through a formal collaboration with Prof K.Wu from Polytechnical Montreal.

Green RF Electronics

This project will consist to develop alternative RF electronics for future generation of RFID or wireless systems that could be wearable, implantable and compatible with a sustainable development. It will be chosen to explore the potentialities of nano-ink previously described and that have shown fantastic capabilities and the ink jet processes associated with heterogeneous integration process (Flip chip, bonding…) to form wireless components together with sensors, actuators, energy sources for the first generation and to form full wireless systems in the second generation on plastic and on paper substrates. We have to emphasize that this project will involve know-how and competences accumulated in previous project but also know-how and competences exhibited by other research teams of the laboratory (M2D, N2IS, ISGE) and it will be tried to transfer "conventional micro and nanosystem" into "green and bio compatible micro and nanosystem".

Smart Wireless sensor Network

This project will be in line with previous works that have been achieved during the last period and is splitted into two alternative approaches. The first one will propose to introduce more intelligence both at analog and digital level and to continue the miniaturization of the components and sub-system as well as the combination of hardware and software architectures through enhanced collaboration with other research teams of the laboratory (i.e TSF and OLC).
Concerning the hardware part, research will focus on the implementation of IR-UWB and MB OFDM transceiver using 65 nm and 45 nm CMOS processes to minimize the power consumption and to be able to have on the same chip the front end, the based band up to the MAC layer. In this context, we plan to have a contribution to the Nano-Innov initiative "project Nano-com" where different transceivers will be design and tested in the 6-8 GHz and 60 GHz range. In order to introduce more intelligence at the analog level, it will be used the works done in the field of active antenna using MEMS and through a 3D integration it will be demonstrated a smart 60 GHz wireless network that will find applications for "in flight" entertainment functionalities.
As previously described in the activity report, the future period will address the development of smart sub-millimeterwave (up to THz) by integrating RF MEMS on top of SiGe BiCMOS or advanced CMOS technologies (65nm or 45 nm) for ultra high bit rate applications and high resolution imaging for medical and security applications. Previous works have demonstrated the capabilities to fabricate passive and antennas on top of 160 SiGe based transceiver as displayed in figure 4 through a collaboration with University of Toronto (Prof S.Voiginescu) that will be amplified in the future.

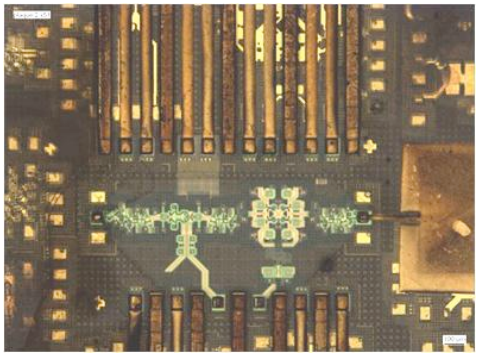


Figure 4 : above IC antenna for a 160 GHz SiGe transceiver

Concerning the based band architecture, research will be continued to validate the concept of reconfigurable radio in term of Bit Error Rate, Modulation Scheme, power consumption, localization and synchronization and to implement it from FPGA to ASIC. More precisely, special attention will be paid to MAC layer being able to sustain high synchronization level with an ultra low power consumption. It has to be pointed out that co-design approach will be carried out in order to insure an interoperability between the different building blocks. The originality of the researches done is related to the strong coupling between electromagnetic simulation, hardware implementation, software implementation and the physical deployment of the network to validate the architectures chosen. Figure 5 gives an example of the network that will be set up to monitor in real time the pressure level on an aircraft wing.

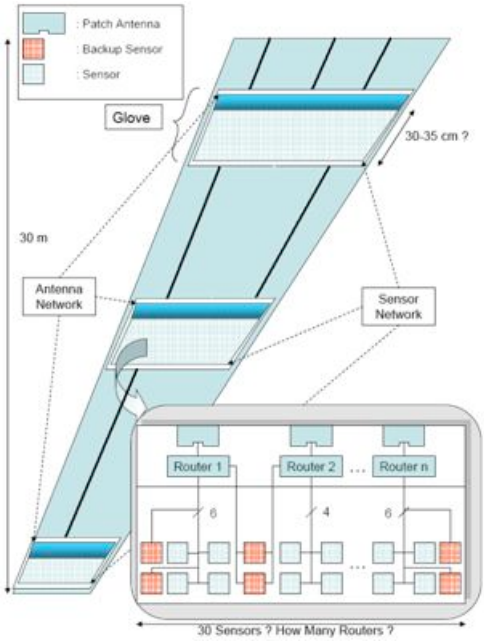


Figure 5 : Example of the architecture that will be envisioned for real time pressure monitoring

Concerning the researches at higher level of complexity, they will be conducted in collaboration with TSF and OLC research groups and will concern the implementation of appropriate protocols supporting both analog and digital intelligence (i.e RF MEMS based antennas) and featuring an enhanced power consumption and investigations concerning the reliability and the security of the network itself. This latter issue will be performed through two approaches. One "analog" approach consisting to identify the failure mechanisms of the different nodes and to rely on the reliability of the network. This will involve the exploration of two concepts listed below :

- The built in self sense node
- Self prognosis of the network

This activity will be extended at the software level by checking the sensitivity of the wireless architecture with respect to fault injection, security and integrity of the wireless link.

The second approach will focus on the continuation of the exploration of the radar reader that has been validated and that needs to be consolidated on real sensors (pressure, chemical, dosimeter, strain gauge…). In parallel, the existing radar will be improved by adding functionalities and by increasing the frequency (i.e multi-frequency) in order to demonstrate the concept of both reader and identification for a large number of sensors. In this context, a collaboration is going to be formally initiated with Georgia Tech Atlanta and contacts have been initiated with Industrial Partners (Rockwell & Collins, AIRBUS) and with end users to use this concept for abandoned wireless sensors network for aeronautic, space, defence, environmental applications (nuclear waste monitoring with ANDRA agency) and medical applications for which we are believing that all the technologies and architectures that have been already demonstrated will be easily useable to propose some breakthrough for medical instrumentation in term of portability, resolution, selectivity and cost.

Advanced simulation and modeling for complex wireless systems

The last project deals with the researches that are conducted in the field of simulation and modeling from material to system level. The activities that are scheduled are organized as follow into five topics :

- RF MEMS/NEMS process simulation
- Multi-physic simulation issues
- Electromagnetic modeling and simulation
- VHDL-AMS modeling and simulation
- Wireless network modeling and simulation

"RF MEMS/NEMS process simulation" — This topic will use all the data accumulated in the different technological development and using the very advanced test set available (AFM, profilometer, nanoindenter..) to propose models taking into account strain, gradient of strain in order to be able to predict the RF MEMS/NEMS process with a better accuracy and to anticipate future components resulting from strain engineering (i.e MEMS based dosimeter, MEMS based temperature sensor..).

"Multi-physic simulation issues" — This topic has been initiated five years ago through the simulation of capacitive and ohmic contact at the material level taking into account the surface states and roughness. The future works will concentrate on the multi-scale issues in order to be able to simulate the contact from nanoscale to device scale. The knowledge will be largely used to propose new material, new architecture to optimize the performances and the reliability of the RF MEMS/NEMS contact.

"Electromagnetic simulation and modeling" — This topic will address both the simulation and the modeling of multi-scale structure from nanoscale to large system. The activities are articulated around the simulation for devices, circuits and systems involving RF MEMS and multiple states (i.e RF MEMS based Reflect array) where in house simulator based scale changing technique will be used and enhanced to introduce process dispersion and reliability issues. For more complicated structures, a coupling between this method and a 3D TLM method will be done to give more flexibility to the designer. For more complicated structure involving larger number of components or a larger number of states, it will be continued to deploy the two electromagnetic methods on a grid computing (GRID 5000 network) and to work closely with computer science searchers (in

MRS group) in order to propose new algorithms of computation to accelerate the computation and improve the convergence problems.
Concerning the electromagnetic simulations at a system level, we are aiming to model the channel propagation in an open space and in a closed space for different applications (i.e aeronautic, space, environment, medical). As an example, figure 6 shows a tunnel that will be used for future nuclear waste and for which it is targeted to propose an optimized distribution of the wireless architecture.

Figure 6 : example of a structure that will be simulated to deploy the wireless architecture

Other activities will address the electromagnetic simulation for automotive applications and for medical applications.

"VHDL-AMS modeling and simulation" — This topic is strongly related to all the activities previously described and will address the development of VHDL-AMS model for both RF MEMS, sensor including reliability (done in collaboration with N2IS group), RF front end. Preliminary works have demonstrated the possibility to develop VHDL-AMS model of MEMS based phased shifter and this will be extended in the future up to the entire front end previously described (IR-UWB, MB OFDM) and will be also coupled to VHDL modeling for the digital building blocks.

"Wireless Network modeling and simulation" — This topic will concern the last step in the simulation chain aiming to model and to simulate the deployment of the network itself with various numbers of nodes, various architectures. The originality of the approach is related to the fact that all the models previously described will be compiled to take into account the physic of sensor, the electromagnetic propagation, the power consumption, the type of communication (IR-UWB, MB-OFDM…). This will be done with GLOMOSIM simulator coupled to MATLAB platform in order to propose the best suited wireless architecture taking into account different requirements following the applications targeted.

The two last sections of the future works will address the industrial partnership and international partnership that will be considered for the future period.

Industrial partnership

For the future period, the industrial partnership will be organized into different actions. The first type of action will concern the exploitation of the competences accumulated to target industrial applications in the field of aeronautic, space, defence, automotive, environment and medical. In this context, the future period will see new collaboration with Rockwell & Collins, AREVA.
The second type of action will focus on the support of LAAS to spin-off start up using the competences developed within LAAS. In this context, it will be considered to support the creation of the start-up 31 degrees in the future period through the creation of a commercial RF MEMS foundry for aeronautic, space and defence applications.
The third type of action envisioned deals with the creation of a joint lab with NovaMEMS company in the field of test and reliability of MEMS/NEMS devices.

International partnership

During the past period, it has been developed numerous European collaboration mainly through AMICOM network of excellence and this has resulted to a joint laboratory with IMT Bucarest and IESL forth in the field of smart MEMS and the future period will be used to run this laboratory and to be better prepared for future European projects and be able to propose a real critical mass for more ambitious projects.
With United States, two main collaborations are envisioned with Purdue University (Prof D.Peroulis) on the physical simulation of RF MEMS and with Georgia Tech University (Prof M.Tentzeris) to develop wireless reader and RF devices on paper. With Canada, two collaborations are foreseen with University of Toronto (Prof S.Voiginescu) in the field of THz MEMS based imaging systems and with Polytechnical Montréal (Prof K.Wu) on the exploration of SIRW technology for wireless sensor. Finally, with Asia two collaborations are envisioned with Taiwan to develop RF systems using both vertical and lateral carbon nanotubes and with Seoul University of the exploration of multi-ferroic materials for new tunable RF devices.

Nano Engineering and Systems Integration – N2IS –

Twice a year, our group organizes a strategic positioning retreat. The following paragraphs present the N2IS medium term (four years) and longer term (2020) roadmaps taking the strategic axis of the lab "Interactions with living organisms" and "Sensor Networks" into account, but also topics, which are in our own domain of interest.

Context and Challenges

Our scientific strategy targets two questions:

- What are the economic challenges of tomorrow's society?
- How micro-nano technologies will contribute to the development of new concepts?

We are thus committed to designing micro-nanosystems, and engineering networks of autonomous and communicating micro-nanosystems adapted to a broad range of applications. Our research scope is guided by Toulouse research environment, which gathers the AESE and CBS national poles of excellence that are specialized in aeronautics and space, and in cancer and health, respectively. In concordance with the national research program Nano-Innov, our interest in the development of nanosystems and on their integration is central, as they constitute the future high-value industrial components. This orientation appears particularly relevant because standard silicon technologies are rapidly transferred to low-cost manufacturing countries.

Our **strengths** lie in the complementarity of our pluridisciplinary competencies, which cover the full spectrum for micro-nanosystems design and integration. Our team is also complementary in terms of human resources with a flat age pyramid (one or two of our colleagues are going to retire, the next not until more than fifteen years), and a good CNRS vs. University researcher ratio (60% CNRS). At present, a relatively low number of researchers validated their HDR (60%), but we expect that at least three group members will obtain this degree in the coming four years. Our **weaknesses** come from our lack of knowledge in chemistry and biology, which is necessary for the development of new materials and biological systems, and which is actively compensated by the establishment of local partnerships. In addition, because we are clearly identified in the industrial network of Toulouse, we are increasingly solicited by manufacturers in support for their own projects, and thus distracted from fundamental scientific questions that remain fully open for nanosystem developments. This drawback is balanced by the financial support offered by industrials, which insures a good financial stability to our group, and allows us to fund at least two PhD per year on our own budget, and hence freely define our own scientific orientations.

Major research orientations and projects

N2IS strategies

The originality of the N2IS approach lies in the synergy of 4 complementary research directions.

- We wish to combine predictive and multi-scale tools for physical systems modeling with simulation tools of multi-functional systems in order to provides solutions for the construction of new transducers or structural components.
- We develop building blocks for "Advanced micro-nano systems" based on polymer materials and with advanced specifications. We focus on thermal actuators, fluid engineering and mixing, MEMS-based metrology, and MEMS-based energy sources.
- We intend to design and prototype compact "Micro-nano fluidic systems" for bio-chips, lab on chips, and for advanced instrumentation in biology.
- We devise embedded Microsystems networks for "health" monitoring, which are deployed ubiquitously in the environment (ambient intelligence) in the form of autonomous, distributed, communicating systems in charge of monitoring and diagnosis.

Atomic scale modeling

We are interested in the modeling of ultra-miniaturized nanosystems, and in this general frame we wish to focus on the integration of biomolecular materials. The control of the conformation and function of biomolecules after their integrationis of paramount importance in the bio-inspired research field and for the development of future nanobiosystems. Our objective is to launch a leading activity in the modeling of biomolecular interactions and their integration into nanosystems following our promising results on the predictive modeling of biomolecular flexibility.

To achieve this goal, we will develop further on our original Static Mode method following two methodological directions:

- insertion of the Static Mode method into more conventional modeling strategies for blind predictions of Bio/Bio interactions (virtual screening, pharmacology applications...),
- development of a specific multi scale approach tothe treatment of bio/non bio interactions.

In this latter case, it is essential to collaborate with experimentalists in order to validate each step of the modeling procedure. We intend to provide a rational understanding of experimental data and to give a rational ground for the design procedure of nanosytems. Because collaborations are mandatory, we already established an intra-group network for nanosystems applications (see Energetical Materials, targeted programs on DNA nanotechnologies and fluidic systems for neuro-degenerative diseases), and initiated external collaborations for expertise in:

- modeling (PUF, University of Southern California, P. Vashista),
- advanced characterization techniques (University of Texas, Dallas, Y. Chabal; LPPMOrsay, G. Dujardin) and chemists and biologists (LCC, IPBS and IRD-PSNPR).

Advanced MEMS

Our commitment is the design of innovative systems built around MEMS for applications in microfluidics or structural health monitoring. Our efforts are focused on:

- the exploitation of nano materials to build nano scale energetic layers applied to autonomous sensors/actuators systems,
- the improvement of 3D assembly techniques,
- the development of sensors / actuators,
- the reliability predictive modeling of these assemblies and metrology applications.

"Exploitation of nano materials" — We have demonstrated that it is possible to build nano scale energetic layer directly integrated on a chip with enhanced performances, high portability. For the next 5 years, the goal in nanoenergetics is to fabricate multi functional nanoenergetic layers that produce tunable pressure spanning kPa to GPa, tunable heat to reach 200-3000°C, and chemical species on demand. To achieve this goal, we will put in common our expertise in simulation at the atomic scale and in virtual prototyping to optimize the energy stored in micro devices and its release. We intend to develop:

- technologies to get atomically-precise energetic materials with exquisitely defined geometries to optimize and control their stability, sensitivity, energy and reactivity. Experimental parameters that should be controlled include the spacing of thermites as e.g. Al/CuO, the barriers between them, and their assembly. Two approaches either based on Physical Vapor Deposition or DNA technologies will be followed (section III).
- Electronics & nanoenergetics integration to produce High Energy Density MEMS. We will work on the conversion of energetic material chemical energy into other forms of usable energy with high yields to obtain ultra-miniaturized, smart, energy free platforms. Applications for wireless sensors networks for security will be explored.

In 5-10 years, we should provide insights on:

- New tunable "molecularly-built" and "atomically-precise" nano energetic layers integratable into MEMS device.
- New computational tools for the understanding and the design of energetic layers.
- New concepts of High Energy Density

This research program will be funded by national civil and military programs. A collaboration with American Universities (UTD and USC) has also started in 2009.

"3D assembly techniques and polymers" — In the "More-than-Moore" framework, we develop 3D integration processes based on stacking with vertical interconnections. The number and length of these tracks is reduced as much as possible, and the feasibility of a coating with a polymer in the form of "Known Good Rebuilt Wafers" combined with through Silicon via and printing process will be explored. We will also continue our researches with SU8 polymer and develop printing bumps deposited with lead-free solder type 5 and 6 (pitch <100µm).

In the frame of ophthalmic laboratory CNRS-Essilor PixCell, we will focus on adaptive optics combining silicon with polymer using electrostatic thick resin or electrostatic and compliant polymers. The second track, breaking with the more conventional approaches MOEMS, proposes the use of functional polymers acting within the meaning of optics and not based on the movement or mechanical deformations.

"Thermal actuators/sensors" — Thermal suspended PN junction sensor/actuators (S_V=-50mV/°C, S_I=20%/°C) will be improved by developing a process allowing a total liberation of the structures. These sensors will be buried in structures, such as composite materials so as to monitor and diagnose defects.

"MEMS and Metrology" — The preliminary results in collaboration with LNE lab showed that the MEMS structures are relevant for the attainment of secondary source of tension. AC voltage reference of low values (under 10 V) in a frequency range from 50kHz to 10MHz and DC voltage reference with feedback control loop are under development with an objective of stability under 10^{-6} V/year. The principle will be extended to new function for micro systems applied to metrology like alternative-continuous converters, micro-meters and power sensors, sources of energy and generators based on MEMS.

"Micro-nano fluidics integration" — During the past 4 years, the microfluidics activity has

significantly gained in strength, and we have improved our skills in technology, fluid engineering and biophysics. Starting from these competences, the N2IS Group road-map aims at addressing the three main following issues.

"Multifunctional fluidics for complex media" — The first aspect of our project is related to the management of complex fluidic media,which are the most common samples in biomedical analysis or environment.
The separation of species of interest remains a bottleneck that limits the integration of miniaturized total analysis systems. The strategy we propose takes advantage of our ability to implement multi-functionalities in a single microfluidic platform. We will provide generic tools to separate, concentrate, sort, and visualize in 3D a wide range of species from macromolecules to cells and colloids. In particular, we propose to develop magnetic, dielectrophoretic, geometric integrated sorting modules, and concentration gradient generators as "chemical sorters". The target applications are paludism, Alzheimer disease, and the detection of pollutants in environmental issues.

"Diphasic microfluidics and optofluidics" — We wish to use microfluidics as a new technological mean for obtaining functional materials structured at the micro and nanoscale. Our approach relies on diphasic microfluidics with the controlled generation of organized networks of micro bubbles or droplets inside micro channels. Among the applications of these micro structured materials, optofluidics devices appear particular relevant for dynamic and tunable diffraction gratings.

"Nanoscale fluidics" — The scaling down of microfluidics to the nanometer scale will be further developed, as we believe that nanofluidic systems offer new functionalities due to exalted mechanisms at the nanoscale, e.g. solid/liquid or biomolecule/surface interactions.
We first aim at progressing in the fundamental understanding of nanoscale flows driven by evaporation, or wetting, thus providing insights on flows in porous media, for which nanofluidic channels are good models. Scaling down would also enhance the potentialities of the diphasic structured materials previously mentioned.
In the long-term, our understanding and control over nanofluidic technologies will allow us to realize integrated complex systems, in particular for biology and the parallel manipulation of single biomolecules.

Systems for Structural and Human Health Monitoring

During the last 4 years, we have developed sensor network applications based on a basic node with an accelerometer, a module for recovery of vibratory energy, and algorithms for identification, diagnostics, and multi sensory learning habits.
We will continue this work in collaboration with industrials for aeronautical structures monitoring and elder home maintenance by focusing our efforts on:

- the recovery and harvesting energy
- the development of a network node combining sensors for constraints, accelerometers, and piezo modules
- the development of a concentrator in conjunction with Brazil (University of Curitiba).

"Energy harvesting" — The piezoelectric transduction has been chosen by N2IS because it requires no outside source of power other than the input signal, and offers a high sensitivity. The main disadvantages are the difficulty in integrating a good piezoelectric materials into a standard MEMS process flow. In the coming years, we will therefore focus on the integration of piezoelectric based harvesting devices integrating massive PZT ceramic with polymer based technology to reduce the device cost, and improve the performance of transduction to meet the applications requirements.

"Structural Health monitoring" — Structural Health Monitoring and reliability validation of composite structures used in aerospace is of paramount importance. We are involved in two projects for blade monitoring with RATIER Figeac (2008-2011), and for the control of defects in structures of aircraft fuselage with EADS, LETI, TARMAC AEROSAFE (2009-2012). The last aircraft crash unfortunately confirms that real time networks of sensors capable of locating and identifying defect in structure are necessary. We intend to combine our thermal sensors based on PN junctions to measure constraints, piezo electric transducers for energy harvesting, and accelerometers with statistical analysis of responses to a mechanical solicitation. Our goal is to design the node and the basic strategy for identifying the defect in a meshed network.

"Home systems" — Elder home maintenance taking care of their healthcare needs gives an enormous impulsion to the development of home automations that teems with the creation of the national Center « Autonomy and home keeping for patients », in which we plan to actively participate. We will diffuse our experience in the domain by contributing to the book « Batiment & domotique ».In this context, our prospective is:

- To transfer the know how obtained in the Ergdom and Prosafe projects into the Homecare project validated in the frame of TecSan ANR 2009.

- To extend our indoor supervision expertise towards outdoor applications, which necessitate new developments in sensors and networks. We have already launched projects on identification and localization by physical modules, and we are improving our diagnosis software with a model describing patient motions.

We are tackling the larger problem of « Home services and supervisions systems », including the health dimension. Robust technologies for complex systems design, modeling and fabrication are yet to be found, and the establishment of collaborations with others partners inside the LAAS - we plan to actively participate to the ADREAM transversal project - and outside LAAS are mandatory.

Implication in the main projects of LAAS strategy.

Our laboratory has identified two challenges:

- **Sensor networks and ambient intelligence**

Our roadmap related to Structural and Human Health Monitoring has been discussed in section II.4.

- **Interaction with the living**

The micro/nano biosystems that we devise in the clean room facility have to meet the standards of biology and healthcare, which constitute a cornerstone that can be reached only with fruitful collaborations with biologists and progresses in instrumentation.

N2IS researchers also think that the next ten years will be the battleground for new bio-inspired technologies, which will be applied to advanced materials, and to the integration of micro-nano biosystems. Our strategy is to strengthen our competencies in integrated microfluidic systems for biology and biochemistry by setting up :

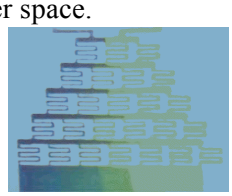
- **Lab on chips and modeling applied to neuro-degenerative diseases and cancer.**
- **DNA technologies for nano energetic materials structuration.**

Lab on chips for healthcare and biology: Application to Neuro-Degenerative diseases and Cancer

Although microfluidics increasingly appears to be a powerful tool for pharmaceutical parallelized studies and point-of-care diagnosis, it remains seldom used in pharmaceutical applications. We thus propose to use our competencies in micro-nanotechnologies and multi-scale integration to fabricate new generations of Lab-on-Chips dedicated to the life sciences. Two different applications are targeted. First, **Alzheimer disease** is a major public health issue, in which the aggregation of the beta-amyloid protein results in the formation of fibrils that leads to cellular death and neuron destruction. Fibrils are metallo-proteic complexes, and the kinetics of their formation remains poorly characterized using standard molecular biology tools. We intend to develop new microfluidic devices for high-throughput studies of amyloid aggregation kinetics.

Second, **deregulations that occur in cancers** are often associated to anomalous replication programs, i.e. the duplication of the genetic material does not follow the pathway observed in normal cells. There is a critical lack of robust and fast methods for replication mapping, although these techniques may provide significant information for cancer diagnosis and treatment.

"Lab-on-Chips developments" — Concerning the Alzheimer disease, we intend to design a generic microfluidic Lab on Chip to screen reaction parameters based on the controlled generation of concentration gradients (Fig. 1a). This microfluidic approach has numerous advantages: it will allow for a dynamic, parallel and automatic screening of physical and chemical conditions, such as the effect of metallic ion concentration on beta-amyloid aggregation over a wide range of time-scales. Temperature sensors combined with electrostatic and magnetic actuators may be added to acutely monitor reaction kinetics and extensively explore the reaction parameter space.



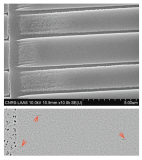


Fig1a: Microfluidic system for gradient generation
Fig1b: Nanochannels etched in silicon, and DNAs stretched in these structures are observed by fluorescence

Nanotechnology processes for the fabrication of parallel arrays of nano-channels have been implemented, and complete fluidic networks involving micro to nano fluidic interfaces have been integrated. Our approach for genome-wide mapping of replication patterns is based on the spontaneous stretching of DNA in nano-capillaries of ~100 nm in diameter (Fig. 1b). DNA stretching can be monitored by tuning the dimensions of the channels, which are associated to different levels of confinement. The manipulation of DNA molecules inside nanochannels is achieved by applications of electric fields. Hence, new multi-scale platforms are under development to perform analytical operations adapted to life cell applications.

"Towards integrated systems" — Our micro and nanofluidic systems are packaged to make them compatible with microscopes. Standard fluorescence microscopy measurements are indeed carried out to observe molecular species in real time. We are also currently developing advanced spectroscopy tools to

monitor the dynamics of biomolecules with exquisite temporal resolutions. Our platforms are thus multi-functional devices in which fluid flows, electric fields, temperature, and fluorescence are monitored in real time. For Alzheimer disease, we intend to sort amyloid aggregation products, and probe the effect of these pathogenic structures on living cells in the presence of specific drugs. In the context of replication, the interplay between replication deregulations and the resistance of cancer cells to specific drugs could be tested in order to improve patient treatments.

"Modeling" — Our approach is multi-scale. First, with atomic scale modeling, we proceed to the calculation of structural parameters using quantum ab initio models and/or empirical classical potentials as a function of system sizes and the presence of weak bonds. Second these results are used to detail structural aspects of the initial interaction steps resulting from peptide/peptide and peptide/metal ions interactions. Reaction pathways can be deduced, and their associated thermodynamic parameters and kinetic constants can be derived and compared to experimental data. Finally, the large scale deformation of macromolecules can be described based on our Flexible tool. Predictions relevant to understand the interaction between macromolecules and nanostructures, in particular the effect of confinement on molecular flexibility and reactivity, will be obtained and used to guide the fabrication of nanobiosystems. These different computation methods will be coupled to obtain a framework that provides fine predictions directly comparable to experimental results.

"Partnerships" — External collaboration established with LCC and IPBS in Toulouse will allow us to devise systems that will fit to the modern requirements of biology.

DNA technologies

Recent progress in chemical and physical control of 2D and 3D DNA assembly have enabled the fabrication of nano-objects, which demonstrated exquisite properties for a variety of applications spanning from Raman spectroscopy, DNA-based computing and material science to quote a few. Given the acute control of assembly processes at the nanoscale, we believe that DNA based technologies, as part of a more global "Bio-Inspired" research frame, pave a way to the development of new generations of nanosystems. So far, despite the richness of this emerging field in terms of applications, DNA nanotechnologies have seldom been used for developing functional systems, and N2IS intends to fill this gap.

"DNA as a template for systems integration" — The principle of DNA origami consists in using multiple small DNA fragments as staples to direct the folding a long DNA scaffold. This process that involves one single mixing step was ushered in owing to computer assisted design. The resulting nano-components, involving length scales from 0.3 nm (one DNA base pair) up to ~1 µm. The DNA origami strategy appears particularly relevant for integrating new generations of molecularly built materials with improved functions.

"N2IS DNA proposal: sensors and energetic materials" — N2IS group proposes to explore this challenging field of research in support of two mainstream group activities. First, we intend to use DNA technologies to fabricate new generations of smart embedded nano-energetic bio-inspired nanosystems. First step will be to contact two reactive nanoparticles, such as Al/CuO, which release a large amount of heat under heat stimulus. Nano-particles of arbitrary size distribution made out of nearly every metal can be found on the market, but their integration by bottom-up assembly remains a challenge that may be overcome using DNA nanotechnologies. Second, short DNA sequences, called aptamers, can be obtained with highly specific chemical functions directed against nearly any target species. Because the integration of DNA fragments in MEMS involves standard biochips protocol, aptamers are believed to be powerful candidates for the realization of new highly sensitive sensors. The design of microfluidic platforms seems to be highly valuable for the large scale integration of DNA components in functional systems. In addition, modeling has been a key ingredient in the success of DNA origami, and we believe that the development of predictive tools will be decisive for the design of robust DNA-based nanosystems.

"Partnerships" — Given the multidisciplinary aspect of this project, we are constructing a network with researchers from LAAS MINAS pole and several French institutes (CEMES, CPMOH, IECB, ITAV, CEA).

Microwaves and Opto-microwaves for Telecommunications Systems – MOST –

Context and Challenges

The context of our future investigations is very close to the one described in our activity report. Our work will mainly remain in the field of embedded material systems for communications, with applications to space telecommunications or to lower cost applications, such as public communications or sensors. What is changing is either the system complexity and versatility, or its operating frequency, or the performance required to lower the emitted power and increase the system reliability.

Concerning the field of space communications, the goal of reducing the satellite size and weight will involve a higher integration level in circuit design, with the ability to design real systems on chip (SoC) without giving up in terms of performance or reliability. It will also involve new techniques in signal distribution and control, such as the introduction of the RF over fiber technology in the satellite. As the devices increases in number in a chip and reduces in size, the noise and reliability problems are more and more important, particularly in embedded systems. It is thus necessary to be able to investigate on all these problems, not simply focusing on the noise in a given active device, or on the system architecture, but being able to describe the system at different levels, going down to device level when necessary.

Toulouse city is clearly situated at the heart of aeronautics and space in France, with the related "pôle de compétitivité". Our aim is to bring to the RF system engineers working in this field the new technologies, the new modeling approaches and the accurate characterization approaches (in noise and reliability) which can only be developed in the frame of public research, and to provide to our students a competence in those fields in order for them to be immediately efficient if they choose to join this industry.

However, the techniques we develop may also be used in different application fields than RF space technology. Firstly, the availability of relatively low cost silicon circuits in the millimeter wave range open the way to a large field of applications for public communications in this frequency range. In the field of microwave optics too, devices are available now to build complete systems at reasonable cost in this frequency range, such as radio over fiber links or high spectral purity frequency sources. Some of these systems could reach frequencies above 100 GHz, where many applications are still at their beginning, such as imaging systems, sensors...

To reach these goals, new modeling and design approaches are necessary. These approaches will combine time and frequency simulation, electrical and electromagnetic simulation, microwave and optical simulation… They will probably start at system level, and go down to device level. They should include the models of the new devices available and be able to deal with analog and digital parts of the system. They should also include a clear strategy for system on chip (SoC) design.

Finally, our expertise in measurement will remain with a strong involvement in the LAAS characterization platform. For our group, the word "characterization platform" is however not really appropriate : part of our work is to design new measurement benches, particularly in the field of noise, and this activity will surely go on.

Major research orientations and projects

We will detail the major research orientations in each of the three main scientific fields of the group. Of course, some of the projects are transverse to these fields, particularly those involving noise studies and circuit design or the modelling of noise in microwave-optical systems…

Electrical noise: from single device to complex system

The excess noise in nanoscale structures will be one of our future works. Nanoscale devices works with much less carriers than conventional devices and any local perturbation will induce a relatively high level of noise. This could have a negative impact since electrical fluctuations will be the ultimate limit of integration for nanoelectonics and represent a very difficult problem in nanoscale sensors and resonators. The reliability of these new devices is also a challenge for a future integration of these technologies in industrial applications where a high level of reliability is required. The low frequency noise is an attractive tool to perform these studies and our experience in this field would be very beneficial. The quality of other new materials, such as diamond and graphene layers, will be also studied using excess noise characterisation.

The managing of noise in complex systems will be investigated in terms of performance and reliability. Noise in heterogeneous systems, including

microwave and optical carriers (see paragraph *Generation and distribution of microwave and millimeter wave signals using optics*), nanostructured materials, analog and digital devices, strong nonlinearities, signal shaping and detection… will be studied with a particular emphasis concerning the noise modelling at device level, circuit level and system level.

For ultra-low noise detection, new types of solutions will be investigated using this philosophy: what are the best devices to achieve simultaneously long-term stability and microwave noise performance of the radiometer? The reliability and robustness of AlGaN/GaN HEMT-based technology will be also investigated using original tools including neural networks and multi-physics simulations. The microwave noise performances of robust GaN-based amplifiers will be assessed when they operate in a complex electromagnetic environment. The impact at system level of theses studies is very important since the architecture of the future receivers could be greatly simplified.

Cyclostationary excess noise issues, that occurs under large signal operation when the time-varying operating point modulates the low frequency excess noise generated by bias-dependent noise sources, will be adressed in a variety of RF devices in order to establish precisely the physical mechanism that is involved and how it impacts the noise performance of some specific circuits (detectors, comb generator, mixers, oscillators, switched filters,...).

Noise in analog and digital SoC will be also examined. The first goal is to be able to simulate the noise in these circuits, and to take benefit of these simulations not only to optimise the circuit performance but also to investigate on reliability at system level. To this purpose, experimental approaches will be developed, either based on global noise measurements of a circuit, or using dedicated antennas to investigate simultaneously on noise and CEM performance on a chip. These investigations will involve a CEM research team in INSA Toulouse, which may join our team to develop a characterization platform at circuit level for reliability. Together with this experimental approach, a simulation approach will also be developed, including the assessment of noise, stability and CEM parameters in an integrated circuit.

Finally, for some devices, an integrated noise test bench will be designed on a chip, but this approach will be described in the next paragraph.

Advanced design and integration of microwave circuits and SoC

The research activity in the MOST team on the topic "Advanced design and integration of microwave circuits and SoC" will continue to address the three levels: materials, components, and circuits. In the first two levels, we will focus on new materials able to greatly improve existing passive components by some kinds of post-processing which need to be developed. These new materials and post-processing procedure will also involve some new characterization methods to be established. The researchers involved in this topic are currently collaborating with a chemistry laboratory to study the integration of a very new kind of ferromagnetic and dielectric material taking benefit of metallic nanoparticules. This material offers new insights in the development of reduced-dimension passive microwave components. By changing the shape and/or the composition of the nanoparticules, the resulting material can also be integrated into nonreciprocal passive microwave components, such as highly integrated circulators and isolators. The activity is currently focusing on the control of the deposition of a nanoparticles-based-thin-film and its characterization in terms of its electromagnetic properties. The next step will be the material integration into planar passive components, either in order to decrease the dimensions or to enhance the high frequency response. Then, the improved components will probably imply that the usual architectures using these components shall be modified to take full advantage of their enhanced characteristics, leading to optimized circuit topologies. Some forms of this new material can indeed be used to reduce the electromagnetic interference inside densely integrated systems.

Climbing in frequency, together with climbing in complexity, is also one of our objectives. Many applications are under development in the millimeter wave range (above 30 GHz), and need both complex and high performance circuits to be developed, such as balanced receivers or low noise frequency sources.

Concerning the digital circuits, we will continue our work on the digital direct frequency synthesis (DDS). At the present time, most of high-frequency DDS suffer from high consumption and cannot be used in embedded systems. We will work on low consumption and high frequency DDS, together with the idea we have patented: the application to UWB pulses generation. Because of the wide versatility of DDS, many other applications of this circuit are possible, and may be investigated.

Our activity on integrated test benches will continue after the promising result of our first realization: the BAW-based phase noise test bench. Indeed, the metrological expertise of MOST group in conventional (macroscopic) test benches can be used to integrate other kind of test benches. Integrating a test bench very close to the devices to be measured,

on the same technology, open the door to intelligent reconfigurable systems, able to characterize any parameters without any external devices and their high associated costs. Such integrated measurements can also help at stabilizing systems or compensate for any kind of fluctuations including noise through closed-loop. Finally, these SoCs can help in the characterization of nanoscale devices (and on sensors based on these devices), for which the extraction of the signal on a macroscopic test bench is often a problem.

Finally, an extension of these studies could be the integration on chip of complete software radio systems, with high capabilities for reconfigurability. These SoCs, of prime interest for future telecommunications networks, should include digital signal processing approaches, complex modulation protocols and self-test techniques. They could be developed in collaboration with signal processing or network communications research teams.

All these topics address a wide frequency spectrum from RF to millimeter-wave frequencies for existing or future applications.

Generation and distribution of microwave and millimeter wave signals using optics

The research on microwave generation using optics has widened our activity on low phase noise microwave sources, and the related modeling of noise under nonlinear conditions in active devices, which has been for a long time one of our important research topics in the group. It is of course a more difficult challenge because it requires a good knowledge and modeling approaches for both electronics devices, optoelectronics devices and also, for some optical devices such as high Q resonators and fibers.

The application field of optical microwave generation is wide, and goes from time and frequency applications to telecommunications, radars and sensors. Depending on the application, the performances of the optically generated signal will differ, but the approach will always be based on a frequency stabilization technique. Once the signal generation is realized, the distribution is performed thanks to the exceptional performances of the optical fiber technology, both on short distances in embedded systems or relatively long distance in other applications.

As pointed out before, in the field of satellite systems, fiber optics will replace coaxial cables for many tasks because of its low mass, small diameter and its immunity to electromagnetic perturbations. As an example, the fiber can easily reach an antenna, or all the elements of an active antenna, or distribute the reference oscillator signal in the satellite. It is therefore important to firstly optimize the performance in terms signal and noise of such links, but also to try to take benefit of this transition to the optical domain to design some original systems in which the signal generation, shaping and processing can be performed in optics with a better performance than at microwave frequencies.

Other application fields for this technology are radio over fiber, particularly in the millimeter wave range were low cost and efficient systems still does not exist, and also the generation of signals in the THz domain (above 100 GHz).

Finally, optical sensors based on the shift of the resonant frequency of a high Q optical resonator are particularly interesting for biological applications. Their exceptional sensitivity rely on the high Q factor and on the thickness of the active layer which is in the range of the optical wavelength.

Our goal is to work on all these fields by optimizing the earth of the system: the microwave optical oscillator, based on a high Q optical resonator.

We will study various techniques to assemble 3D ultra high Q factor optical resonators, in parallel with our work on ultra high Q resonant fiber loops. We will optimize electrical optical oscillators (OEO) based on these resonators thanks to an original modeling approach which is still under development, and which takes into account simultaneously the 1/f noise components of the optical and the electrical devices. We will include these OEOs in complex systems in which they are associated to a reference oscillator, and considering two cases : the frequency reference is performed in the microwave domain or in the optical domain (optical clock). We will try to climb in frequency and to develop OEOs in the millimeter wave range, were the equivalent microwave Q factor will be enhanced. To this purpose, original modulation techniques are under study, together with the possibility to couple these OEOs to millimeter wave range dual mode lasers (mode locked lasers). Also, we will try to take benefit of the nonlinear effects in these resonators at high optical power, and to investigate on tunability techniques.

Finally, the problem of biological sensors based on optical WGM resonators will be investigated in collaboration with the LAAS groups which have developed a technology of biologically sensitive layers. The extreme sensitivity of such a resonator to any change on its surface, even if the sensitive layer is thinner than one micron, together with our knowledge of low noise frequency discriminators and oscillators should allow us to design an efficient sensor.

All these projects will be performed with the teams having the complementary knowledge required to design such complex systems. The microwave optical systems for aeronautics and space applications will be developed with Thales and CNES. The clock systems or the use of an OEO in a synthesis chain could be part of a project with a time and frequency laboratory. The development of optical resonators for sensing will be performed in collaboration with different research groups at LAAS, including photonic group.

Microdevices and Microsystems of Detection – M2D –

Context and Challenges

During the second part of the last century, research efforts in electrical engineering have been responsible for amazing advances related to electronics, microelectronics, computer sciences,… Thus, since silicon technologies have allowed doing smaller, better and cheaper, and have found many commercial applications for the "Information/ Communication", "Aeronautic/ Transports", andor "Confort/Leisure" domains. Nevertheless, even if it is regularly delayed, the end of the ITRS roadmap will always arrive too early. It has therefore been necessary to detect new opportunities of developments and new technological break-through. The first one is related to the microtechnologies: it proposes to extend the silicon success story not only to electrical engineering but also to physics, chemistry and biology, leading to the realisation of microsystems. The second one deals with the nanotechnologies: it aims to realise elementary functions using nano-objects and to prepare the next technological revolution.

For the years 2011-2014, the M2D research project will still lay within the frame of the micro/nanoelectronics and micro/nanotechnologies developments for the "Information/communication", "Aeronautic/Transports" and "Health/Agribusiness/ Environment" domains (figure 1). It will of course be focused on the group core activities, i.e. the silicon-based and polymer-based technological research dedicated to the study of integrated material and related processes, to the integration of specific microdevices and to the realisation of detection microsystems. Nevertheless, nanomaterials and nanostructures will be also explored in order to achieve the full potential of new nano/microdevices.

To deal with these different challenges, the M2D group is relying upon its wide-range skills and know-how in term of technological research, going from the integration materials/processes to the (micro)systems realisation. However, this scientific wide area has its reverse side. Indeed, technological research is known to be time-consuming and to require adapted manpower. Today, the lack of institutional permanent positions associated to recruitment problems has prevent the M2D group from reaching the critical mass especially for research topics related to the development of detection microsystems. Fortunately, during the last few years, the M2D group has been able to attract permanent researchers from other laboratories, and to welcome long-term visitors from industry. These opportunities of scientific mobility will be favoured in the future in order to reinforce specific research activities and/or to compensate some priceless retirements and departures. From another point of view, since it is worth one third of the LAAS microtechnological realisations, the organisation and the improvement of the LAAS technological platform are real opportunities of development and excellence for the M2D group.

Finally, even if some of them are not specific to the M2D group, threats are in huge numbers. They are concerning the lack of permanent positions (researchers, engineers and technicians) in order to support the research in technology, the increase of non-permanent positions (PhD and postdoc students) finally responsible for important salaries expenses as well as skills/know-how losses every two or three years, the multiplicity of project calls in order to finance and valorise scientific researches, as well as the perpetuation of the LAAS technological platforms in terms of equipments renewal, technical support and availability.

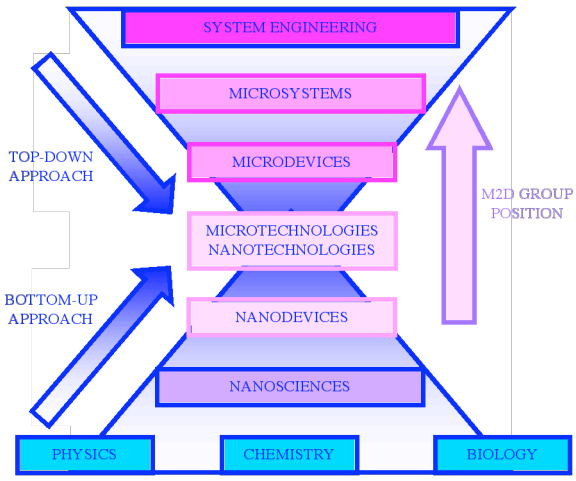


Figure 1: general position of the M2D group project

Major research orientations and projects

Studies concerning the M2D main research topics, i.e. CVD processes, doping technologies, microlithographic processes, pressure microsensors, chemical microsensors in gas/liquid phases, will be carried on. Nevertheless, the M2D prospect will emphasize four major research orientations, respectively dedicated to the integration of new materials, to the development of nanostructured microdevices and/or nanodevices, to the study of new detection/transduction principles, and to the break-through towards "flexible and/or plastic micro/nanotechnologies based on organic materials".

CVD processes for the integration of high-K and/or piezoelectric oxides

The CVD skills and know-how will be oriented towards non silicon-based materials, and more especially for the integration of high-K dielectrics and/or piezoelectric materials. This is related to the purchase of dedicated CVD equipment for the LAAS technological platform. Two technologies, respectively related to organometallic chemical vapour deposition (OMCVD) and atomic vapour deposition (AVD) are being compared in order to be able to integrate metallic and perovskite oxides in the frame of the development of metal-insulator-metal (MIM) capacitors, radiofrequency MEMS and MEMS-based actuation and/or detection microdevices. In this frame, for the deposition of ternary compounds, the major issues are the reproducibility, the control and the uniformity of the deposited layers. Compared to the other techniques available, the AVD technique presents the advantage of highly conformal layers, allowing the fabrication of complex 3D structures. OMCVD processes may also offer the possibility of conformal layers, and this technique allows the deposition of thick, i.e. micronic, layers, which are often required by microtechnological application (piezoelectric layers for MEMS-based detector/actuators for instance).

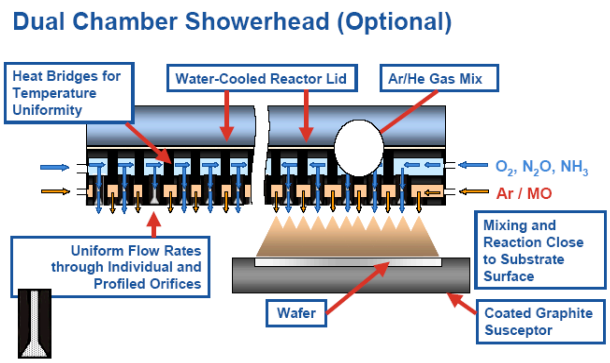


Figure 2: scheme of the AIXTRON – KEMSTREAM OMCVD furnace showhead

Doping technologies for germanium and germanium-rich SiGe alloys

One of the major MOSFET miniaturisation issues is the decrease of their intrinsic delay, i.e. the increase of their drive current. In current device generations, this is achieved by applying global or local strain into the channel in order to increase the carrier mobility. However, scalability issues, associated especially to local strain methods, will probably make these solutions insufficient for future technology nodes. This has therefore called for a shift from process-induced mobility enhancement solutions to the direct use of high-mobility substrates. Germanium, with its four times higher hole mobility compared to silicon, is one of the primary candidates, especially for PMOS transistors. However, although the highest mobility would be on pure Ge, the devices on such materials may suffer from relatively high off-currents. One way to limit such effect is by increasing the energy gap with the inclusion of some Si in the Ge. An additional reason of the interest on Ge and Ge-rich SiGe alloys is the lower thermal budget needed for device fabrication This opens the possibility of fabricating 3D monolithic structures where Ge-based devices are fabricated on top of Si devices with a further increase of density and shorter interconnects.

A main obstacle against a break-through of this technology is that the research on germanium virtually stopped about forty years ago and re-started only recently, so that incomplete information is available, for instance, on the doping of germanium. As for Ge-rich SiGe alloys (above 60%), the doping of this material is still a relatively unknown field. However, considering the recent success in obtaining thin Ge-rich alloys on insulators using the condensation technique (i.e. without use of thick buffer layers), the interest in this material system is growing fast.

Within this context, we wish to reinforce our research activity on the doping of germanium-based materials and/or substrates. According to our skills and previous knowledge we will work *(i)* to acquire fundamental knowledge on the physical mechanisms that control the doping process of germanium and Ge-rich SiGe alloys and *(ii)* to identify the best process conditions for an optimised fabrication of ultra-shallow source/drain junctions in these materials. In particular, we will focus on the study of implantation-induced damage accumulation and amorphisation, recrystallisation, extended defects evolution during annealing, and their impact on dopant diffusion and activation (figure 3). This activity will be carried out in close collaboration with CEMES Toulouse, LETI Grenoble and IISB-FhG Erlangen.

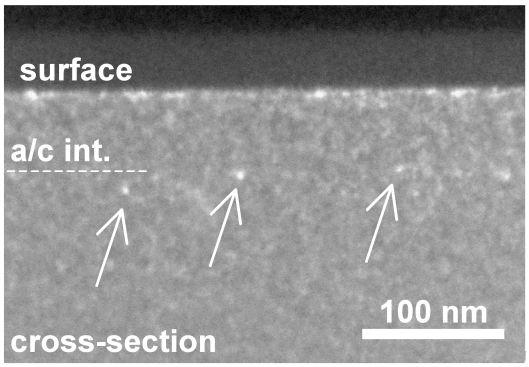


Figure 3: End-of-range defects in pre-amorphised Germanium ultra-shallow junctions

3) Silicon-based optical microdevices

The results obtained in terms of emission by 300K light emitting silicon nanocrystals (reproducibility, control, 6'' wafers technological transfer on LPCVD and rapid thermal annealing systems), allow us to consider in the very short term the fabrication of diode type components based on such materials (figure 4). Two research axes can be emphasized.

"Materials and device optimization, by tuning of the fabrication process parameters, in order to obtain high electroluminescence efficiency" Besides, we focus our attention on electroluminescence devices: choice of transparent front electrode (indium tin oxide, zinc oxide, polymers…), improvement of efficient electrical carrier injection in silicon oxide… while correlating photoluminescence, conduction mechanism and electroluminescence properties.

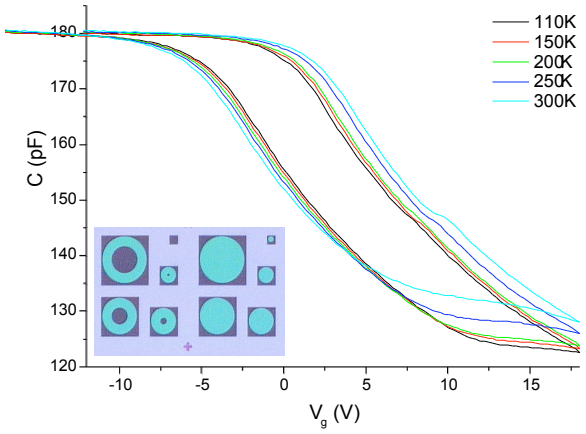


Figure 4: temperature-dependent C-V characteristics of nc-Si-based MIS diodes for electro-optical and electrical tests

"Create silicon-based light sources to develop a biosensor" — The aim is to develop the basic design and adapt this element in the micro-analysis system also composed of waveguide structures, a detector and a fluidic microsystem. Test structures where the optimal geometry is studied will be fabricated in order to test the configuration that provides the highest optical power. This includes the characterization and optical performance of the process materials in terms of lifetime, power consumption, robustness, tolerance and response time. Once the sensor has been optimized, it will be integrated into the optical-based fluidic microdevice developed within the M2D group (cf. section 8), tested and modified to ensure the best possible performances and satisfy the (bio)chemical and biological analysis requirements.

Nanowire-based microdevices

Semiconducting nanowires (NWs) are foreseen as building blocks for the fabrication of nanodevices offering a large number of possible applications. Efforts are already being undertaken to integrate silicon NWs into devices and sensors although their physical characteristics are far from being controlled and sometimes even not understood. Indeed, nanowires can be used to realise nm-size (L_g< 20 nm) gate-all-around devices, which offer better electrostatic control of the channel over planar devices. Moreover, following a surface functionalisation, NW-based sensors offer an increased sensitivity with respect to conventional planar devices, thanks to the increased "surface-to-volume" ratio of the active surface. Independently of the foreseen application, one prerequisite condition for the success of NW-based devices is the mastering of their growth, doping and conduction behaviour.

Thus, our group wishes to develop a research activity aiming to asquire fundamental knowledge about the growth, doping and transport properties of silicon nanowires. Following preliminary studies carried out in collaboration with the NBS group, NWs will be grown using the "bottom-up" CVD-based VLS method. Our experience in CVD helped us to find optimal conditions, for which surface reaction of silicon on gold is preferential. We found a process temperature (470°C) enabling the growth of undoped or in-situ boron-doped silicon-nanowires. This allowed the elaboration of a PN junction in the nanowire, the N zone being obtained by arsenic implantation. Our experience allows us to say that in situ phosphorous-doped Si-NWs are feasible with similar process conditions than boron-doped ones; leading to the elaboration of transistors. This activity will be supported by an extensive use of structural characterisation techniques based on Transmission Electron Microscopy.

In parallel, we will also investigate the dopant activation and the electrical transport properties of the grown Si-NWs. Their electrical characterisation will be done using specific test structures that allow the electrical addressing of single nanowires. These structures will be fabricated by a combination of conventional and advanced techniques, such as Electron Beam Lithography and Focused Ion Beam. An example of a preliminary test structure fabricated at LAAS is shown in figure 5. This activity will be carried out in close collaboration with CEMES Toulouse GPM Rouen, and IEMN Lille.

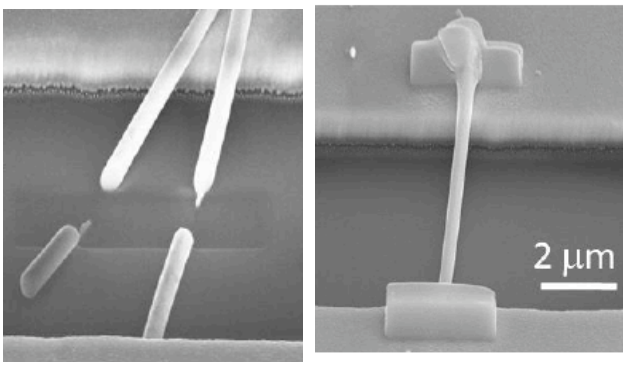


Figure 5: TEM pictures of silicon nanowires

5) Nanomaterials integration by inkjet printing

Studies concerning microlithographic processes will be focused on the development of inkjet printing techniques. Indeed, since it is compatible with the liquid-phase integration of nanomaterials, this process is promising for the development of new microtechnological platforms and new microdevices architectures.

Two research axes will be considered. The first one concerns the integration of metal oxide nanoparticles (ZnO, SnO_2, ...) for gas sensing applications. The main objective is the deposition at low cost, high speed and high level of reproducibility of different sensing materials on a single microhotplate or on a multisensor platform. This technique will allow us integrating various materials at wafer level without using additional photolithography steps. An example of preliminary test is shown in figure 6.

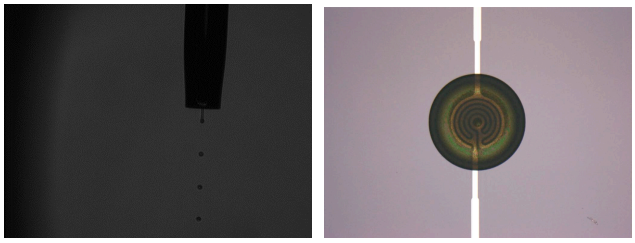


Figure 6: deposition of ZnO nanoparticles by inkjet for gas sensor applications: drop jetting and deposited layer

The second axis is part of the collaboration with the MINC group. It concerns the integration of nanomaterials for radiofrequency applications. In collaboration with the CEMES and CIRIMAT laboratories, it has been decided to work on iron oxides Fe_3O_4 and Fe_2O_3 nanoparticles as well as on carbon nanotubes. Researches will aim to the study of the nano-based layers electromagnetic properties and to the realization of radiofrequency microdevices. Nevertheless, specific attention will be brought to their integration onto flexible substrates (papers, plastics, others,…) in order to go towards the development of new technological platforms for radiofrequency identification (RFID), communication and/or detection microsystems.

RF-MEMS transducers for powerless detection microsystems

During the last decade, in collaboration with the CISHT/MINC group, the M2D group has worked on the realisation of radiofrequency micro-electromechanical systems (RF-MEMS). Today, this fruitful collaboration will be extended to the development of RF-MEMS transducers for powerless detection microsystems and wireless sensing network applications.

This new electromagnetic transduction has been already validated for pressure sensor using planar resonator and silicon membrane, and stress sensors will be soon developed accordingly. The objectives of future works are the optimization of these RF-MEMS transducers for dedicated applications (aeronautic, space).

Three new development axes will be pointed out. First, gas microsensors using electromagnetic RF transduction is just being investigated. The sensor uses a microwave planar dielectric resonator operating at the whispering-gallery-mode. This resonator could be made of dielectric substrate covered by a metal oxide (as SnO_2) thin film as sensitive layer. A gas adsorption makes the SnO_2 effective parameters changing namely its permittivity. This is finally responsible for a resonance frequency shift. Presently, the proof of concept is demonstrated through full wave simulations (figure 7). Then, since their detection principle is based on capacitance variation, electromagnetic RF transduction mechanism will be also investigated for MOS radiation sensors. Finally, the electromagnetic transduction principle will be studied in order to explore biological systems and extract biological information.

All these electromagnetic microsensors will be interrogated using RF radars, in collaboration with the MINC group.

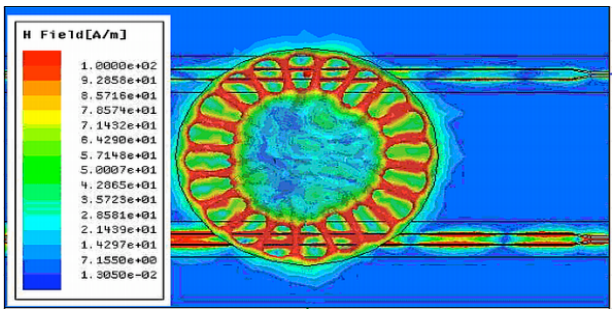


Figure 7: simulation of RF resonator the gas detection

Electrochemical microsensors for the liquid phase analysis

Research activities dedicated to the electrochemical microsensors will be carried on. Thus, the technological platform respectively dedicated to chemical field effect transistors (ChemFETs) and

electrochemical microcells (ElecCell) will be extended to others applications in the frame of the health, agribusiness and environment domains: pH measurement, ion detection and/or biochemical/biological analysis,... However, for the ElecCell platforms and in collaboration with the LGC laboratory, these orientations will still require the deposition of new electrode materials (tungsten oxide, molybdenum,…), the development of new (bio)chemical-sensitive layers, the integration of fluidic microdevices at the wafer level and the realisation of adapted measurement interfaces.
Nevertheless, two new prospects can be pointed out. The first one concerns the ChemFET/ElecCell common integration with a single gate/reference electrode (figure 8). The development of this new device called Electrochemical Field Effect Transistor (ElecFET) is promising since it gives opportunities for new detection potentialities, especially with the extension of the pH-based ChemFET detection principles to oxido-reduction reactions or to the EnFET (enzymatic detection transistor) adaptation to the dehydrogenase enzymatic family.

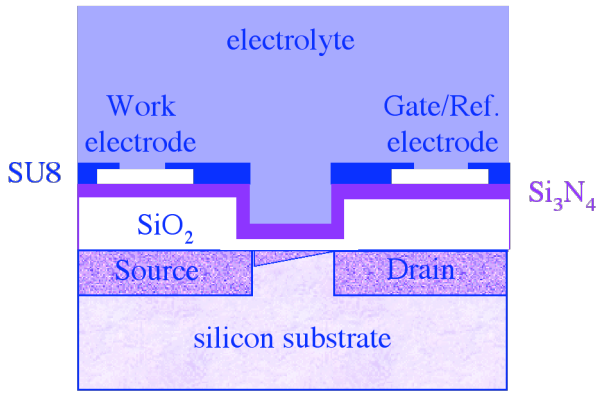


Figure 8: scheme of the ElecFET microdevice

The second one concerns the development of electrochemical microsensors in the frame of the flexible/plastic microtechnologies. Since the ChemFET microdevice has to be integrated onto a silicon substrate, works will be limited to the chip thinning and packaging on flexible substrates (clothes, plastics, others,…). On the contrary, the ElecCell microdevice is fully compatible with flexible technologies. Thus, Through the development of specific equipments and technologies, research activities will involve the integration of metallic microelectrodes (Au, Pt, Ag/AgCl,…) onto organic substrates (PET, PEN, Kapton and/or PI) in order to achieve the realisation of flexible electrochemical microsensors.

Organic microdevices for the optical detection in liquid phase

With the arrival of I. Séguy from the LAPLACE laboratory (Toulouse), the M2D group will extend its activities to the integration of optical transduction principles for the detection in liquid phase. These will concern mainly the development of organic-based and polymer-based technologies. They are relying on the M2D skills and know-how in term of microlithographic processes, but are still depending on the purchase of a specific technological equipment dedicated to the organic materials evaporation and engineering. Researches will be focused on the integration of organic light-emitting diodes (OLEDs) and related organic photodetectors (OPDs) into polymer-based microfluidic devices in order to perform liquid phase analysis (figure 9).
The project will focus on the following aspects: integration, multi-detection, in-line/on-the-spot analysis and field deployment. The OLED and photodetector devices must be optimized by using multilayer architecture with doped transport layer and micro-cavity structure (for the OLED) to obtain high brightness, long term stability, narrow full width at half maximum (FWHM) and correct peak wavelength for emission and detection.
Studies will first be applied to the optical absorbance measurement. Then, they will be extended to the fluorescence and chemical luminescence monitoring. They will be developed in the frame of the flexible/plastic micro/nanotechnologies for chemical, biochemical and/or biological micro-analysis.

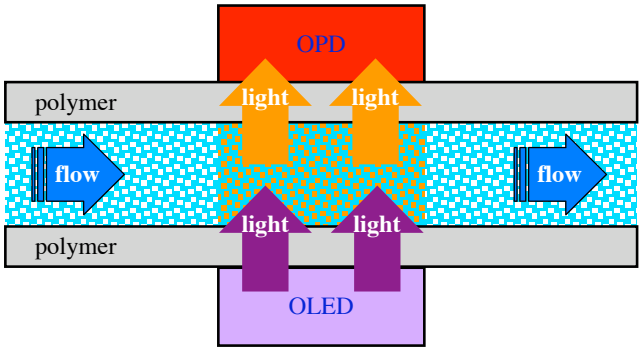


Figure 9: organic microdevices for the optical detection in liquid phase

NanoBioSystems – NBS –

Context and Challenges

By shading a different light onto the biological and the physical world, scientific research has the capacity to radically impact our world. Amazingly, basic research, primarily driven by intellectual curiosity rather than immediate applications, often has long-term impact. As an example, the quantum theory issued at the very beginning of the last century from the physicists community opened up ways towards "vital" inventions like the transistor, the lasers, and speeded up our technological progress. A few decades later on, by unraveling the intimate of the DNA molecular structure, biologists started the genomics revolution.

Should we expect same kind of groundbreaking innovations from a Biology/Physics-related disciplines alliance? Our group is more than ever committed to give a positive answer to this question. This pattern resolutely fits into one of the future mainstreams of our laboratory (*Interacting with the Living* strategic orientation) as well as into the general strategy of our governing institution (the ST2I CNRS Institute, the *Engineering for the Living* research axis).

For sure, the path to successful results is neither straight nor short. Cross-disciplinary research requires consistent long-term (financial and human) investments, willingness to address high-risk topics (and to accept the risk of failure), as well as perseverance. It also requires new ways of thinking about both biological and physical worlds which necessitates tremendous efforts to speak and understand each other language.

For the years to come, the NanoBioSystems group scientific road-map is made of new exciting challenges rather than incremental approaches on existing basis. Besides the excitement of exploring new lands and pushing further the existing frontiers, our road-map is mainly motivated by the mature level of some of our key developments which are now sold (or about to be sold) to private companies (see DiffraChip and Bioplume projects in the "*Past research*" document). This strongly motivates our will to focus on new topics while empowering our confidence in the future.

Our future challenges are thoroughly driven by state-of-the-art key issues which are nowadays at stake in the nanobiotechnologies-related disciplines:

1. How could we interface living cells in order to explore/exploit their energy-producing capabilities?
2. Which is the best way to integrate functional nanobiomachines?
3. How could we impact/detect the conformational change at the unique protein level in order to better understand the response to external (chemical, biological, environmental) stresses?

Specific projects (in collaboration with biologists and chemists) will be set-up either at the national or the international level to address these issues. Before digging into the general orientations of future projects, a SWOT[1] analysis specific to our group has been done to evaluate at best (by now) the internal and external factors that are favorable and unfavorable to reaching our common goals. The results of the analysis are given below:

Strenghts (internal):
- *Human resources (permanent positions) continuously increasing (+266%) since the group's creation*
- *An actual interdisciplinary group which members are experiencing a strong identity feeling (reinforced by weekly seminars, monthly enlarged scientific councils, annual meetings)*
- *Strong synergistic work with the lab's technical services*

Weaknesses (internal):
- *Lack of bio-Infrastructures in-house*
- *Lack of technical personnel with skills in biology and chemistry*

Opportunities (external):
- *ITAV and Canceropole emergence*
- *Group members representativity at the international (conference steering committees – IEEE of MEMS, MNE…) and national level (Research Body or "GDR" responsibilities, CNRS representative etc.)*

Threats (external):
- *Difficulties to recruit highly qualified students for PhD projects*
- *Perpetual funding research that weakens our scientific operational activities and threatens the PhD students' supervision quality.*

In the next section, four major research orientations (and corresponding projects) are declined following the same general scheme: *Motivation*, *Main goals*, *Ways to reach those goals* and *Partnership*.

[1] Strengths, Weaknesses, Opportunities, Threats

Major research orientations and projects

The future research orientations of the NanoBioSystems group will respectively address: *neuron-chip interactions*, *functional nanobiomachines*, *living cells real-time imaging* and *thermal biochips*. Even though the projects will be distinctly overviewed, strong interactions between the corresponding project teams will be key in successfully reaching the final goals. Yet such interferences were so far the success recipes of our group.

Neuron-chip interactions

"Motivation" — Extracellular electrical interfacing of cultured neurons has been implemented with planar metal electrodes on insulating substrates and with semiconductor devices, such as transistors and capacitors, in silicon chips. In both cases, the activity of a nerve cell – i.e. the action potential – is stimulated and/or recorded by interfacing individual nerve cells with electrical microdevices that locally generate and/or sense electrical field variations. So far, the most elegant way to "communicate" with nerve cells or to make them inter-communicate has been achieved by Fromherz group, on the following principle: (i) neuronal activity is elicited by capacitive stimulation from a silicon chip and (ii) neuronal activity is recorded by a transistor located on the same chip. Nevertheless, the signal-to-noise ratios were in general not large and in some cases it was not clear whether recordings were from single cells or from groups of neuronal cells. Inspired by Fromherz's seminal work [Fromherz, 1993], C. Lieber's team recently demonstrated enhanced signal-to-noise ratios using arrays of nanowire field-effect transistors integrated with the individual axons and dendrites of live mammalian neurons [Patolsky, 2006].

"Main goals" — The aim of this project is to operate a paradigm shift in the neuron-chip interfacing issue by means of piezoelectric nano(electro)mechanical systems. The piezoelectric materials, like the neuronal cells, have a dual behavior in that sense that they convert mechanical solicitation in electrical signals and vice versa. Though simplistic, the previous statement might represent, if concretized by efficient physical coupling between a neuron and a piezoelectric mechanical microstructure, a significant step forward in the fundamental comprehension of how external stimuli are conveyed and interpreted by nervous systems, at the single cell level. For this to be successfully achieved, several steps have to be reached:

(a) being able to generate (mechanically and biologically) stable 2D neuronal patterns onto a solid surface;
(b) sensing and harvesting the neuronal action potential using a piezoelectric microdevice (sensor);
(c) eliciting the neuronal action potential by piezoelectric charges electrostimulation subsequent to the mechanical solicitation of a piezoelectric device (actuator).

"Ways to reach the goals" — We propose to design and fabricate arrays of micron-scale membranes integrating piezoelectric layers which in turn will be properly functionalized (by electrochemically grafted polypyrrole layers bearing neuron-specific antibodies) so that individual neurons may be placed individually onto each device. Prior to the neuronal culture, the chip surface may be pre-patterned to initiate guided neurites growth from one neuron to its neighbor [Merz, 2005]. The sensing capabilities of the piezoelectric layer will enable real-time monitoring of the forces exerted by the neurons on their respective anchoring sites during the growth process which in turn will help to unravel the starting point of the neuronal net mechanical instability.

Once the biological interface between neurons and piezoelectric MEMS optimized, we will demonstrate the active interfacing in two steps: first, at the neuron-microdevice level, second at the neuron-neuron level *via* the associated microdevices. At the neuron-microdevice level, an action potential will be elicited by capacitive electrostimulation using the direct piezoelectric effect, or the actuation function. The subsequent objective is to feed-back the elicited action potential into the microdevice thus causing its deformation by reverse piezoelectric effect. In this way, the "firing" moment of the neuron would be translated into a mechanical action. At the neuron-neuron level *via* the associated microdevices, we intend to further demonstrate the signal transmission from a piezoelectric micromembrane to another through a pair of neurons. In this case, the action potential would be elicited by a micromembrane, then transferred through topographically guided neurites to the neighboring neuron and finally sensed/harvested by the associated microdevice. Figure 1 schematically depicts the final set-up aimed by the project.

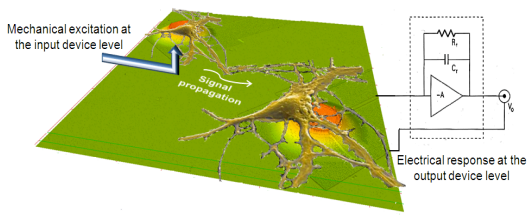


Figure 1: Schematic picture of a two-neurons network interfaced by a mechano-piezoelectrically active substrate.

Analytical modeling will be thoroughly performed in order to couple the electrical model of the Transductive Extracellular Potential (TEP – current flow through the neuron/silicon junction [Fromherz, 2003]) and the electromechanical model of the piezoelectric micromembrane. If rigorously performed, this phase of the project will subsequently generate efficient input for the associated electronics design and fabrication.

The analytical modeling will be completed with finite element analysis thus benefiting from the computation capabilities of the method in order to provide, at the end, exhaustive modeling of the whole system (including fluidic, electronic, biological and electromechanical aspects).

"Partnership" — Potential partners in the frame of this project would be teams with complementary background i.e. surface biochemistry (*Chimie pour la Reconnaissance et l'Etude des Assemblages Biologiques led by Thierry Livache, CEA Grenoble*) and neurophysiology (*Traitement des informations visuelles led by Serge Picaud, Institut de la Vision, Paris*). Preliminary discussions have already been engaged and potential common interests have been identified.

Functional nanobiomachines

"Motivation" — Nature offers today thousands of machine at the nano-scale, working in symphony within any living organism on Earth [Mann 2008]. This basic analysis shows that biology can be seen as a nanoscale phenomenom. Molecular biology, genetics and biochemical methods have been extensively used for studying the structure and principle of these bio-machines from their in vivo observations to their in vitro extraction and purification. Since the pioneering work of C. Montemagno [Montemagno 1999], a new paradigm has thus been proposed; we call it "Nanotechnologies from biology". The idea is to integrate natural nanoscale bio-machines on devices in order to exploit their exceptional efficiencies. This methodology can be seen as a rupture with respect to the conventional "top-down" and "bottom-up" approaches, because here, the engineering of the active part of the device is devoted to nature rather than to human conception. Two major improvements are expected that are related to basic functions of natural organisms: power supply and motility. Indeed, living organisms are expert systems for generating autonomous power from their environment through specific molecular machineries and are capable of movements. In this project we develop a novel generic method for integrating natural nanoscale machines onto artificial surfaces processed through silicon technologies. We focus our attention on the integration of a nano-motor with the ambition to demonstrate the efficiency of this bio-inspired method compared to conventional MEMS or NEMS top-down approach. However, our method is far more general than the specific case of the assembly of a nano-motor and can be easily generalized to any specific bio-machinery as far as the genetic components of the involved proteins have been or can be identified. The nano-machine that has attracted our attention for its importance in the living cell is the Bacteria Flagellum Nano-Motor (BFNM). Despite its size, 45 nm at the largest, it propels its host in the media by rotating at high speed a long external filament. The interest of this machine for nano-systems is huge since, if correctly integrated on a miniaturized device, this bio-nano-machine give to it efficient motility. The BFNM is emblematic of what we described before, its inner structure and mechanism is still unclear and subject to acute controversy and its integration onto artificial devices is seen as a relative far dream.

"Main goals" — Our ambition is to investigate a methodology for assembling the Bacteria Flagellum Nano-Motor ex-vivo, on an artificial engineered surface. We will address both questions of the elucidation of its structure and mechanism and its integration in 2 or 3 dimensions on a solid support. This work is a fundamental research which would serve as a base for the future development of the new area of integrated hybrid bio-inspired devices. The main innovation in our approach will be the coupling of synthetic biology (proteocell technology) with nanotechnologies (soft-lithography).

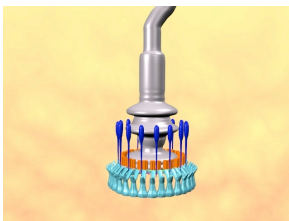


Figure 2: Schematic picture of the BFNM isolated form the cell membrane. The largest diameter of the C-ring (blue) is 45 nm

"Ways to reach the goals" — Our approach is currently a mix between two concepts: Integration and Investigation; "Integration", because we have to generate surface conditions where the BFNM basal body could self-assemble; "Investigation" because the analysis of this assembly will reveal the architecture of inaccessible parts of the motor (such as the cytoplasmic C-ring structure) and later on the inner mechanism of the motor.

In order to reach the objective, the workplan can be divided into three 3 main and ambitious parts: Large study of the motor protein interactions, Partial 2D reconstitution of the basal body of the flagellar motor into an engineered nano-device and Elaboration and

Integration of Proteo-cells exhibiting the basal body. Each of this part can be divided into three steps: Production of the elementary brick, Device elaboration plus brick integration, here we will focus our attention on the combination of soft-lithography and self-assembly, and finally Observation, here we will make extensive use of AFM in liquid media. Each step is challenging because a major issue is common: the Production, Purification and Insertion within pre-existing phospholipids structure (liposome or Supported/Suspended Bilayer membrane) of membrane or trans-membrane proteins.

"Partnership" — Potential partners in the frame of this project would be teams with complementary backgrounds in protein production (*LISBP team of Pr. J.M. Francois),* synthetic biology *(University of Mineapolis US, team of Pr. Vincent Noireaux)* and AFM imaging (*Institut Curie team of Pr. S. Scheuring)*.

Living cells real-time analysis

"Motivation" — In 1982 Binning et al., made the experimental demonstration of the tunneling effect [Binnig 1982]. A few years latter Binnig *et* Quate [Binnig 1986] described the atomic force microscope which is a powerful tool to study living cells. Indeed, this microscope is based on the interactions between a thin tip and a surface which can be followed in liquid and do not required vacuum. As a consequence, cells are never dried, and can be analyzed in liquid, while alive and at the nanoscale. The research linked to the exploration of living cells at the nanoscale has started at LAAS in oct. 2007 and are currently following 3 mains goals.

"Main Goals" — The first step for imaging living cells by AFM is to achieve a firm but not denaturing immobilization of the biological object of interest. This paradoxal situation implies to develop strategies that constitute our first goal. The cells we have immobilized are yeasts (eukaryotic cells) or bacteria like *E. coli* or *L. lactis*. In the case of yeast cells, the goal is to get a better understanding of the cell wall organization which is a potential target for antifungal agents. As far as E. coli is concerned our biological goal has been to develop an original way to determine if a bacterial cell is dead or alive. Finally, with *L. lactis* we are addressing the problem of bacterial adhesion to surface. In the ongoing project, the goal is to make good use of force spectroscopy (FS) to refine our perception of probiotic bacteria to mucin which is the glycoprotein that recovers the intestine.

"Ways to reach the goals" —To face the immobilization challenge, we use classical methods like mechanical trapping of spheroid cells in porous membrane or electrostatic immobilization of negatively cells on polycation layers. Moreover we develop new methods based i) on the patterning of molecules presenting a high affinity for the cells [Cerf 2009] or ii) on the convective capillary deposition on samples presenting a hydrophilic/hydrophobic contrast [Ressier 2008]. On this subject we have a strong and effective collaboration with Laurence Ressier and Benoit Viallet from LPCNO, UMR5215.

To investigate yeast cell wall organization we are using AFM in contact mode to make images of the cell surface and in the force spectroscopy mode to probe the nanomechanical properties of the cells. The force curves are converted into indentation curves what represents the cell deformation. This deformation can be fitted to a Hertz model in order to measure the young modulus of the yeasts. To evaluate the role of each constituent of the cell wall on its elasticity, we have worked with a collection of mutants affected for the synthesis of each constituent of the cell wall (glucanes, mannanes or chitin). We have demonstrated the crucial role of glucanes but also of chitin which represents only 2% of the dry weight but plays a major role in the cell wall organization. For those experimentations the cells are grown in LISBP UMR 5504 and the design of the research is discuss with JM François.

The intestinal epithelium is covered by a self-produced mucus mainly made of a glycoprotein named mucin. As a consequence, it is of first importance to probe the interaction between potential probiotic bacteria that are *L.lactis* and mucin. To reach this goal we've decided on one hand to develop the cell probe technology. This approach consists in functionalizing the AFM tips with living cells (figure3).

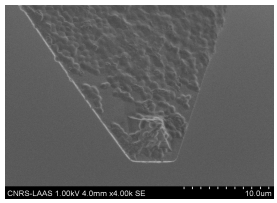


Figure 3: The lacto-probe. SEM image of an AFM tip covered by L. lactis cells

On the other hand we have deposited mucin on polystyrene and have characterized this layer by AFM (surface topography), and XPS (surface chemistry). Finally, we performed force spectroscopy experiments between those two elements: *L. lactis* on the tip and mucin on the PS. Here the cells are grown in LISBP, the experiments are mainly made by Dohan Tam Lam Le (PhD student) and designed in agreement with M Mercier Bonin.

Finally, we will start to work on a new exciting topic in September 2009 dealing with the interaction of a

virus (namely the bacteriophage MS2) with its host cell (here *E. coli*). In this work we will have to combine the ability to gently immobilized living bacteria, with advanced chemistry to functionalize tips with the virus or the attachment protein.

"Partnership"
LISBP UMR 5504: Jean-Marie François, Muriel Mercier Bonin
LPCNO, UMR 5215: Laurence Ressier
LCPME, UMR 7564: Christophe Gantzer
Linz Biophysic Institute: Hermann Grüber

Thermal biochips

"Motivations" — A field in which precise spatial and fast temporal control of temperature hold potential to greatly improve efficiency is the field of fundamental molecular studies. A typical area of molecular studies is that of protein folding [Gruebele 1998]. It is well-known that proteins undergo conformational changes upon changes in their environment. As the incorrect folding of proteins is thought to be the cause of neurodegenerative diseases, including Alzheimer's, Parkinson's, Huntington's, etc., protein folding has become a focus of attention in medical and pharmaceutical research.

Although simulations and structural studies give certain information, the most direct approach to study the pathway and the various transition states of protein folding and unfolding is to perform dynamical studies of the events. In these dynamical studies, it is obviously necessary to have access to a characterization method for the analysis of the molecular events, e.g. fluorescence analysis, circular dichroism or NMR spectroscopy [Righetti 2001]. However, it is also important to have access to a technique which allows for the initiation of the molecular events. Examples of such techniques are rapid mixing (or stopped flow), pH-jumping, pressure-jumping and temperature jumping (T-jumping) [Volk 2001].

In the same context, another important area concerns the recently developed biochip array technology which is perfectly situated to carry out large-scale screening of molecular interactions including DNA-protein and protein-protein interactions. The main problem is that contradictory results can be obtained due to difference in gene expression levels or kinetic properties [Ekins 2003]. Therefore, on-chip perturbations-based approaches are extremely relevant to study both thermodynamics and kinetics of biorecognition events in steady state or dynamic regime [Berthomieux 2009].

"Main goals" — The main objective is to design and fabricate versatile "Nanowire-based thermal biochips" with a striking feature lying in the possibility to modulate the temperature in confined areas (submicrometer scale) with a high temporal resolution (under the µs regime). Apart from the biological-related aspects (protein folding and DNA melting), fundamental studies will be also devoted to heat transfer in confined structures in dry and liquid conditions.

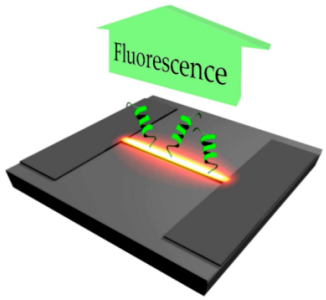


Figure 4: Conceptual sketch for the study of molecular kinetics using nanowire T-jumping. The folding behavior of the green fluorescent protein (GFP) could for example be visualized by means of fluorescence.

"Ways to reach the goals" — Four main aspects should be considered: (i) the fabrication of nanowires using VLS growth or electrolytic deposition into nanoporous membranes; (ii) The optimization of hierarchical assembly of nanowires into functional thermal nanodevices; (iii) The development of dedicated optical and electrical measurements for thermal characterization in dry and liquid conditions; (iv) The study of biological events: DNA or molecular beacon melting and protein folding under thermal perturbation.

Preliminary results have already been obtained for each aspect. Our efforts will be mainly focused on optimizing the coupling between our devices located a microfluidic cell with more sophisticated optical measurements especially two-photon microscopy, fluorescence polarization microscopy and fluorescence correlation spectroscopy (FCS) to combine a high time resolution with long observation times [Zondervan 2006]. From a biological point of view, two different probes will be studied: a DNA switch with two equilibrium states [Viasnoff 2006] and the Green Fluorescent Protein [Wong 2007] to optimize our thermal nanodevices for discriminating thermodynamics and kinetics properties of biological events under fast thermal cycles.

"Partnership"
ESPCI, UPR A0005, Lionel Aigouy
ENSCP, UMR 7574, Michel Mortier
ECP, UPR 288, Sebastian Volz
LCC, UPR 8241, Azzedine Bousseksou

Potential partners :
ENS, UMR 8640, Ludovic Jullien
LPN, UPR 20, Charlie Gosse
ESPCI, UMR 7083, Virgile Viasnoff
Institut Fresnel, UMR 6133, Hervé Rigneault

References

Fromherz P (**2003**) *Neuroelectronic interfacing: semiconductor chip with ion channels, nerve cells, and brain. Nanoelectronics and information technology*, Waser R (ed.), Wiley-VCH (Berlin) 781-810

Fromherz P, Müller O, Weis R (**1993**) *Neuron transistor: Electrical transfer function measured by the patch-clamp technique.* Phys Rev Lett 71: 4079-4082

Jenkner M, Müller B, Fromherz P (**2001**) *Interfacing a silicon chip to pairs of snail neurons connected by electrical synapses.* Biol Cybern 84: 239-249

Merz M, Fromherz P (**2005**) *Silicon chip interfaced with a geometrically defined net of snail neurons.* Adv Funct Mater 15: 739-744

Patolsky F, Timko B, Yu G, Fang Y, Greytak A, Zheng G, Lieber CM (**2006**) *Detection, stimulation, and inhibition of neuronal signals with high-density nanowire transistor arrays*. Science 313: 1100-1104

Mann S. (**2008**) *Life as a Nanoscale Phenomenon*, Angew Chem Int Ed 47: 5306- 5320

Montemagno C. (**1999**) *Constructing nanomechanical devices powered by biomolecular motors*, Nanotechnology 10: 225-231

Binnig G, Quate CF (**1986).** *Atomic force microscope.* Phys Rev Lett 56: 930-933

Binnig G, Rohrer, H., Gerber, C. & Weibel, E. (**1982**) *Tunneling through a controllable vacuum gap*. Appl Phys Lett 40: 178-180

Cerf A, Cau J-C, Vieu C, Dague, E. (**2009**) *Nanomechanical properties of dead or alive single-patterned bacteria.* Langmuir 25: 5731-5736

Ressier L, Viallet B, Beduer ADF, Fabié L, Palleau E, Dague E (**2008)** *Combining convective/capillary deposition and AFM oxidation lithography for close-packed directed assembly of colloids.* Langmuir 24: 13253-13257

Gruebele M, Sabelko J, Ballew R, Ervin J (**1998**) *Laser temperature jump induced protein refolding*. Accounts of Chemical Research 31, 699-707.

Righetti PG, Verzola B (**2001**) *Folding/unfolding/refolding of proteins: Present methodologies in comparison with capillary zone electrophoresis*. Electrophoresis 22: 2359-2374

Volk M (**2001**), *Fast initiation of peptide and protein folding processes.* European Journal of Organic Chemistry 14, 2605-2621

Ekins R, Chu F (2003), *Protein Arrays, Biochips and Proteomics: The Next Phase of Genomic Discovery*, Albala, J.S. and Humphery-Smith, I., Eds., Marcel Dekker, Inc., New York

Berthoumieux H, Antoine C, Jullien L, Lemarchand A (**2009**), *Resonant response to temperature modulation for enzymatic dynamics characterization.* Phys. Rev. E: 79, 021906-021911

Zondervan R, Kulzer F, van der Meer H, Disselhorst JAJM, Orrit M (**2006**), *Laser-driven microsecond temperature cycles analyzed by fluorescence polarization microscopy*. Biophysical Journal 90: 2958-2969

Viasnoff V, Meller A, Isambert H (**2006**), *DNA nanomechanical switches under folding kinetics control.* Nanoletters 6: 101-104

Wong FHC, Banks DS, Abu-Arish A, Fradin C (**2007**), *A molecular thermometer based on fluorescent protein blinking*. Journal of the American Chemical Society 129, 10302-10303

Photonics – PHOTO –

Context and Challenges

Advanced photonic components are essential for a large range of application fields, as optical communications, health, metrology, environment ... General objectives are to push their performance through innovative concepts and process technologies, to advance in miniaturisation and system integration, to master the wide range of optical functionalities, to progress towards system-on-chip and system-in-package integrating photonics. Among recent opportunities, the exploitation of optical phenomena at a nanometric scale, quantum dot and self-organised materials, microoptics, and trends in electronics-photonics convergence open up challenging areas of research with promising breakthroughs in devices and systems.

The Photonics group will carry on with previous activities which lie within the general framework of the nano- and micro-systems for photonics with the key-challenge of integrating photonic systems on a chip. The group will aim at innovative concepts and processes, in particular on generic approaches enabling the design and the fabrication of a variety of devices and complex photonic functions, and contributing to push on the boundaries of photonics integration. The mission of the group is two-fold. We first focus on high performance semiconductor laser sources with the challenge to overcome a key limitation: the lack of any generic approach enabling practical integrated laser systems. The second objective is to explore and validate novel concepts and integration technologies for pertinent architectures of on-chip photonic, addressing all-optical systems or combining photonics with electronics, biology or microfluidics to achieve new sensing or instrumentation capabilities.

Work on semiconductor lasers will remain a central part of our current activity, because many photonic systems depend critically on their performance or their functionality. Vertical and horizontal architectures are actively investigated within the group, as they allow both to extend the know-how in efficient devices, and to make some pioneering demonstrations. Our current interest focuses on GaAs based devices, exploiting the long experience and mastering acquired on these well-established III-V semiconductors to cover a broad research area from the development of original technological approaches to the study of novel optical functionalities and devices. Our skills in design, growth, fabrication and characterization of GaAs-based devices stimulate research projects with the community, and strengthen especially the networking actions within the framework of the French Basic Technological Research Program. Moreover, a long collaborative record has naturally led to bring closer the Photonics group and the IES (Montpellier), and the next common research efforts will aim at implementing advanced nanophotonic concepts in GaSb-based semiconductor lasers.

Priority will be given to breakthrough approaches, exploring unconventional semiconductor lasers based on novel architectures, exploiting the huge potential offered by nanophotonics. During the last years, the group investigated the building blocks in design and fabrication of 2D GaAs photonic crystals, patterned nanostructures and vertical cavity structures. Next developments in fabrication processes and novel concepts will allow us to improve the 3D electrical and optical confinement in semiconductor lasers. We will explore the full potential of photonic crystal approach combined with spatially organized active regions aiming at original horizontal or vertical architectures exhibiting unprecedented advantages compared to present devices. Particular attention will be paid to the ability of 2D CP-based integration schemes to offer highly efficient laser systems integrated on a single chip.

To go further towards efficient laser systems, the group will work on compact extended cavity architectures, offering practical features namely for instrumentation, biology or healthcare. We will target various optical feedback configurations with the emphasis on improving spatial, spectral and temporal emission properties of VCSELs or edge-emitting lasers. Original external cavities, implementing microoptics and frequency filtered feedback will be investigated. The association of the OSE group offers the opportunity of combining our complementary research interests and expertises, to take up a leading position by addressing the double challenge of realizing laser systems on a chip while integrating electronics. The simultaneous achievement of both targets would lead to significant breakthroughs providing smart solutions for a wide range of applications such as sensing, telecommunications and healthcare.

Major research orientations and projects

Molecular Beam Epitaxy for GaAs photonics

A new MBE system will be set up in LAAS clean room in 2010. This system will allow us to grow on 3”, 4” or simultaneously on three 2” wafers with a high spatial uniformity (<1.5% over 4”) and controlled III and V fluxes.

This new machine will first allow us to go ahead on our present research and know-how involving MBE growth in order to reinforce and propose improved or novel performances for GaAs-based device structures containing quantum wells or quantum dots in order to demonstrate ultimate performance or new functionalities. These will be based on novel device design and/or innovative technologies that involve MBE, such as regrowth on PAlOx-treated surfaces and on patterned GaAs. The device structures will benefit from the growth on large surfaces with spatially uniform characteristics and controlled thicknesses of the stacked layers offered by the new equipment. This will be useful for the VCSEL applications in which LAAS is involved (thickness sensitive soliton-structures, multi-functional devices based on feedback in VCSELs), will promote easier comparison of differently processed devices and shared studies of samples. In addition, this will provide the opportunity to study broad area guided structures on GaAs, partly based on original photonic crystal designs, or meet spatial uniformity requirements for heterostructures grown in view of particular applications.

In addition to this activity that extends the skills developed up to now at LAAS, the new MBE machine will allow us to take up new challenges.

First we will investigate on the properties of properly designed III-(As,N,P,Sb) alloys in order to push ahead the material limits encountered in GaAs technology when only the III elements can be varied (Ga, Al, In). This is expected to provide wavelength range extension and improved performances for the devices: one example of such improvement could be the realization of low resistive tunnel junction for the electrical injection in lasers.We will also investigate on these alloys to get access to lower wavelength lattice-mached laser diodes grown on silicon in view to opening up LAAS to III-V technology on silicon and let path new routes towards III-V integration.

Finally, we will study GaAs-based material growth on silicon (/germanium) patterned surfaces using selective growth schemes on dielectric masks or etched silicon wafers with submicrometric scale patterns, on the basis of our work on patterned GaAs. The aim will be to get free-defect strain-relaxed III-V structures by exploring elastic relaxation on patterned silicon surfaces and unstrained growth by promoting growth mode on silicon/germanium surfaces patterned with SiO_2.

Integrated functional architectures for vertical microcavity-based lasers

On the basis of our experience on the VCSELs and associated electrically-pumped microcavity devices we have extensively studied since more than 10 years, and of all the related III-V technological processes, we will exploit our skills on device modeling, AlOx process, surface patterning, electrical injection control, polymer micro-optics, and will take the opportunity offered by the arrival of the MBE machine to propose innovating design and technologies, demonstrated on some selected applications (Fig. 1). Within this framework, we will focus, on the one hand, on tailoring of the device structure itself to make it meet those requirements that provide access for these devices to ultimate performances, multifunctionality as well as novel functionalities. On the other hand, we will develop work on polymer and transparent conductive materials as parts of these devices or as parts of compact integrated VCSEL-based photonic systems. Strategic domains will be aimed: sensing, instrumentation, metrology, biology, health care, communications.

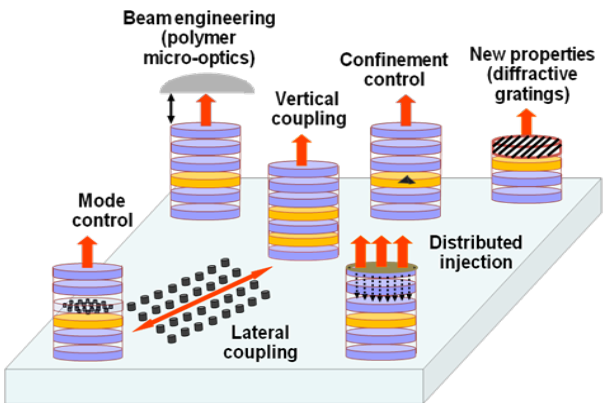


Figure 1: Overview of future work on VCSEL geometries for advanced functionalities

Our project can be sorted out in the following topics:

"Lateral structuring in VCSEL devices" — Several remaining technological limitations have to be overcome to improve the actual performance of vertical-cavity based devices, to enlarge their functionalities and to further extend the spectral window in the GaAs material system. In this way, the difficulty in precisely controlling the shape and the size of the active region from AlOx apertures (formed by lateral selective oxidation of an AlAs buried layer), the possibility of embedding local (sub)micrometric structuration in a layer (active or DBR unit layer) would lead to provide an additional tool to tailor the device structure. We propose to focus our research studies on these issues. First, we will pursue the development of our novel technological process of planar oxidation (PAlOx) close to device active regions, which enables in a very flexible way to structure transversally the refractive indices. This innovating technique allows us to address separately the electrical and optical

properties of these optoelectronic devices, thus leading to novel structures with controlled transverse optical behaviour, we will investigate on. This goal leans on the epitaxial regrowth method we have developed. We will also take the opportunity of our skill on III-V regrowth on patterned GaAs surfaces to apply this innovative process in device fabrication to develop new functionalities for VCSELs.

We will also address the stake of the modal and polarisation control in vertical cavity lasers through a substitution of conventional Bragg mirror by diffractive elements. Despite the substantial reduction of the structure thickness resulting in some performance enhancement, the control of optical properties cited above will be directly implemented by means of integrated sub-wavelength diffractive gratings. The originality of our approach in this case is the use of low index AlOx layers bringing at once advantages of a monolithic and compact structure compatible with electrically driven schemes. This approach will be studied not only on GaAs but also on GaSb substrates for achieving high efficiency emission of VCSELs at wavelengths above 2.6 µm for gas sensing applications (collaboration with IES Montpellier).

"Current injection engineering in photonic devices" — For the lateral control of current injection in vertical cavity devices, we will exploit and combine the unique properties of localized injection schemes through structured surfaces and Esaki junctions. Simultaneously, the modeling of involved mechanisms will be pursued and enriched by considering experimental results obtained on these complex geometry devices. As a few examples, multipath localized injection scheme will be treated alternatively by means of surface patterning and regrowth, localized ion implantation, or localized oxidized patterns (PAlOx process). Note that the improvement and the control of current injection in photonic devices is not only of mandatory interest for advanced VCSEL structures but also for all the broad area electrically pumped III-V devices, such as photovoltaic tandem cells. The realization of these sophisticated architectures will also rely on the epitaxial studies described above, that we will apply to real devices thanks to the new MBE machine.

The association of this transverse structuring with functional materials such as indium tin oxide (ITO) and ZnO films will be studied in view of engineering electrical pumping.

By offering new technological solutions, we will enable to break the gap for more complex devices and open up the way towards new applications. As an example, large area VCSEL remains a very attractive challenge for improving output power, and providing new functionalities such as cavity soliton manipulation. The common line is the generic aspect of the proposed solutions, with the aim of keeping the transfer capabilities to other wavelengths and other material systems.

"New and multi- functionalities" — We will pursue our current studies on lateral detection integrated in VCSELs. These original devices will be of interest for realizing compact and integrated emitting-detecting devices for optical feedback injection based sensors in collaboration with the OSE group. Another solution based on coupled cavity devices is also foreseen. There both transverse or longitudinal geometries for the cavity coupling can be applied. The interest for coupling cavities into VCSEL based devices rose increasing interest with the demonstration of optical parametric oscillator (OPO) or new perspectives in upcoming applications (quantum cryptography, THz generation, external modulation).

"Polymer micro-optics on VCSELs" — We will go further in the design and the fabrication of polymer micro-optics elements to improve VCSEL integration in microsystems. We will develop a novel method to fabricate self-aligned optical micro-elements (micropillars, microtips) onto VCSELs by means of a simple and collective process totally independent of the photolithography alignment accuracy and suitable with device post-processing. The idea is based on the use of the VCSEL source itself to trigger an infra-red photo-polymerization process and give birth to perfectly self-aligned optical micro-elements. This study will be led in collaboration with DPG (Mulhouse) for novel IR photopolymer fabrication and with LNIO (Troyes) for optical simulations and characterizations (NIR Optics ANR project).

To offer a greater flexibility in VCSELs applications, we will also design and fabricate active lenses to make it possible the modification of the optical path during device operation. On the basis on our previous results on SU-8 patterning, we will develop suspended polymer membranes associated to a thermal actuation. VCSEL devices including such an active collimation will be then developed for instrumentation and more particularly for self-mixing interferometric systems in collaboration with the OSE group.

Thanks to these studies, we will develop skills and technologies on polymer materials complementary to the III-V technology we have extensively studied at LAAS. This will allow us to design novel hybrid systems. This would give access to the association of active sections containing polymers on the surface of VCSEL that would lead to a new type of multifunctional coupled sources or integrated

photonic circuits but also to VECSELs (Vertical External Cavity Surface Emitting Lasers) with tunable short cavities formed by a polymer membrane, microfluidic circuits for biomedical systems based on VCSELs, optical waveguides for optical interconnects as well as probes on VCSELs surfaces for near-field microscopy…

Towards planar integrated laser systems

Our main objective concerns the development of photonic crystal lasers to demonstrate disruptive semiconductor lasers and explore their potential for the route to photonic integration. We will focus on all 2D-photonic crystal structures which are very promising for a fully planar integration scheme. We will combine the advantages of the electrical and optical confinement properties of quantum dots and photonic crystals to improve the spatial, dynamic and spectral control of the laser emission.

We will first investigate several architectures to achieve spectral performances beyond the DFB ones. In the frame of the ANR CRISPI project, photonic crystal single frequency tunable laser diodes will be demonstrated in the mid infrared wavelength range. At 1µm wavelength and shorter, we will harness the deep etching of the photonic crystal in GaAlAs/GaAs that will allow achieving electrically pumped 2D all photonic crystal lasers. We will exploit the works on quantum dots and on MBE regrowth on patterned surface to engineer different gain zones inside the device. This will allow the spatial control of the active material along the cavity and the design of new laser structures, especially for applications in the temporal domain. Further challenge will be in compact and monolithic laser systems on a chip embodying the full potential of quantum active regions and 2D photonic crystals (Fig. 2), to answer the new requirements in terms of power and fast sources for applications such as embedded ultimate metrology, high resolution spectroscopy, cold atom physics…

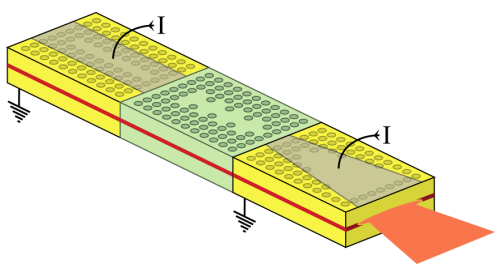


Figure 2: Schematic view of a planar integrated laser system

We will also carry out the exploration of non conventional lasers, based on 2D photonic crystals architectures. We will focus on two different systems.

In the frame of the ANR GLAD project we will aim at the first demonstration of the random lasing action from a 2D active membrane of GaAlAs/GaAs system perforated at the nano- scale. The challenge will be to reach the strong scattering regime of Anderson localization at optical wavelength using a technological approach giving unprecedented control and reproducibility of the random geometry. We will explore the sensibility of the first devices to local perturbation and we will identify the specificity of such random lasers compared to conventional microlasers for new relevant applications.

In parallel, within the ANR CLAC project we will demonstrate and study lasers based on self-collimation in photonic crystal. Our aim is to achieve the first experimental observation of lasing in a self-collimating guide and to study the benefits of such unique guide for laser performances. Indeed self-collimation enables structureless guiding of light (ie without index contrast or band gap effect) and it exhibits both spatial and spectral filtering with very high and interdependent selectivity. We will exploit and refine self-collimated propagation properties to achieve single-mode operation for large lateral extensions of the mode and to study the original ability of the self-collimation cavity to lase simultaneously along two orthogonal directions supporting different spectral modes.

Photonic systems for instrumentation and healthcare

The increasing demand to improve the beam quality, the spectral and temporal characteristics of the laser emission has stimulated the use of external cavity, not only for optical telecommunication systems, but also for sensors, instrumentation, chemical and biological analysis. However, these complex laser systems suffer from unpractical use and limited operating capabilities. Devoted semiconductor lasers, advanced extended cavity architectures, common platform implementing lasers with micro-optics and functional optical devices, compatibility with micro-fluidics for optofluidic sensing or biological applications, electronic circuits for real-time analysis and processing, are among the ways to be explored to provide powerful laser systems and hence more to tackle the challenge of a "fully integrated laser system on a chip". Within the global framework of these complex laser systems, our projects will encompass three types of objectives. The first one is to further pursue the investigations on resonant grating filters to help completing the need for advanced, compact and efficient filters, essential building blocks for photonic systems. The second one proposes to explore real potentialities of innovative frequency-selective architectures jointly implementing devoted lasers and resonant grating

filters, in the practical case of instrumentation and healthcare applications. The third one copes with on chip advanced photonic integration, and proposes generic building blocks integration schemes using key CMOS technologies.

"Resonant grating filters" — We will actively pursue the exploitation of resonant grating filters in the infrared wavelength range, for which we demonstrated state-of-the art-results. We propose to extend to the mid infra-red range the ultra narrow-band and very low polarization dependence performance previously demonstrated in the vicinity of 850 nm. We plan to study a GaAs-based multilayer resonant grating filter allowing operation in the 4-9 µm spectral range, for spatial earth watching. This work will be carried out in collaboration with Institut Fresnel (Marseille) and CNES (Toulouse).

"Optical re-injection in laser diodes" — Spectral performances of laser diodes can be tailored to specific needs by the use of optical reinjection in external cavities. Such external cavity lasers are routinely used for achieving extremely low linewidth semiconductor lasers, for applications such as optical clocks for example, or, on the contrary, to lock a laser diode within the coherence collapse regime, to optimize optical pumping of Erbium Doped Fiber Amplifiers (EDFAs). However, externally stabilised laser diodes suffer from complexity of their integration. We plan to assess the performances of resonant grating mirrors for optical reinjection in laser diodes as their use will provide within one component both the output mirror and the wavelength selectivity needed for external cavities. These studies will be started in cooperation with the OSE group which already masters optical feedback interferometers based on self-mixing effect. We will study original spatial and frequency-selective feedback configurations for better fundamental understanding of the spatiotemporal behaviour of the emission of semiconductor lasers under optical feedback, from a joint experimental and theoretical analysis. These configurations will be applied to develop optimized control techniques ensuring the efficiency of laser sensors based on self-mixing. Particular attention will be paid to the study of emission dynamics and the mechanisms that determine the onset of the coherence collapse.

"In-situ microlab" — Silicon technology is available for monolithic association of various functions like memory, signal treatment, sensing, actuation, RF communication,… leading to smart multifunctional chips or lab-on-chips dedicated to various analyses. However, photonics functions are still not integrated in such systems due the lack of generic and compatible photonic technology. We are involved in the multidisciplinary project MAISOE of the Foundation of Cooperation for Aeronautic and Space STAE that joins several groups of LAAS together with chemists and marine environments teams. This project deals with the development of in-situ autonomous biogeochemical sensors for oceanic environment applications. We plan to study how optics and electronics functions can be monolithically integrated to lead to highly selective and robust chemical sensor dedicated to deep sea-water analysis. Our objective is to demonstrate that such a sensor can be obtained by associating selective sensitive material, optical resonant effects induced by resonant grating filters, photo detection, and electronic treatment on a single chip using a CMOS compatible process. This work will be done in close cooperation with the MAISOE partners.

High Frequency and Fluidic Micro and nanosystems – MH2F –

Permanent Staff:
Members: D. Dubuc (MC), K. Grenier (CR)

Non Permanent Staff:
PhD students: C. Tong

Context and Challenges

This new operation has been launched at LAAS in Sept. 2009. The research activity was initiated for two years in LIMMS-CNRS (UMI 2820) in Tokyo, Japan.

The scientific context resides in pushing further our fundamental knowledge and know-how toward the use of electromagnetic fields for health and life sciences.

On the fundamental aspect, our scientific activity is focused on the interaction of fluids (especially biological mediums: cells, tissues...) on microwave electrical fields.

As far as engineering research is concerned in this operation, (1) the implementation of the RF technique (considered here as ranging from MHz to few 100s GHz), (2) its integration, which takes benefit from micro and nanotechnologies, (3) as well as multifunctional metrologies are addressed.

Such researches are located at the interface of three sciences: high frequency electronic, micro and nanotechnology and biology. Regarding the biological and chemistry (for fluid engineering) aspects, we are in close collaboration with biologists (notably cancer specialists) from Toulouse Univ., from INSERM and with chemists from CIRIMAT (Toulouse).

Based on our international experiences and consequently scientific expertise in RF-based micro and nanosystems for biology, several breakthroughs have been identified:

- rich bio-information contents in RF signatures,
- large availability of spatial and temporal resolution,
- integration capabilities toward Lab-on-a-Chip and "In vivo" approaches
- downscaling toward single cell analysis,
- and high throughput ability (detectors' parallelization).

Consequently, we are launching four main research orientations, which are in advance compared to the international competition. Since 2008, the use of microwave signals to elaborate integrated sensing techniques dedicated to biological and medical applications is emerging but remains indeed irregularly investigated.

Major research orientations and projects

All the major research orientations are established on three platforms, which are dedicated to the design and modeling of RF/fluidic systems, micro and nano integration, and a reliable (in term of bio parameters to be given to biologists) and multifunctional metrology.
Three major researches orientations related to bioengineering will be investigated. They are motivated by the previous listed breakthroughs of the RF technique and are in adequacy with biologists' requirements in term of new technologies for life sciences.
A forth orientation is dedicated to the engineering of microfluidic, which is employed to tune high frequency electronic devices and circuits.

Miniaturization down to single cell

We have already demonstrated the capabilities of the RF technique to discriminated pathological states of cell suspensions (dead, alive, tumorous...). We plan to fully exploit the RF-signature to have access to more and more fine bio-parameters at the cell level. It will imply to down scale the RF-detectors and enhance the sensitivity that will have an impact on the development of the RF-techniques and micro and nanotechnologies. Moreover, a special care will be dedicated to boost the reliability and selectivity level of the experiments.

High throughput capability

The second main orientation, where RF sensing is particularly promising and challenging, consists in a massive integration of RF/fluidic detectors.
The added values reside in the label free ability of the RF technique, combined to real time monitoring capability, which all confers an easy way for implementation and non invasive character. Such non-destructive screenings allied with other cell manipulations like sorting will permit the elaboration of complete non invasive lab-on-a-chips.

In / ex vivo

The integration of the RF technique on new kind of substrates, i.e. flexible polymers, opens the door to in/ex vivo characterization, where conformability on non planar-bio-objects is mandatory. Combined with real time monitoring and contact less capabilities of

the RF technique, it will provide innovative analysing systems for bioengineering.

Besides the targeted biological and medical applications, we also investigate the potentialities of the fundamental and engineering researches for:
1. environment, food monitoring... where electromagnetic interaction with gases/liquids/solids can be adequately exploited.
2. high frequency electronics, where liquid implementation and manipulation can result in signal tunability.

Liquid based tunability for high frequency electronics

Although liquids in optics have already demonstrated tremendous researches and now applications (reconfigurable lens), the combination of liquids and RF electronics is sporadically investigated. Only Purdue Univ. in USA is currently developing this new topic.
The main motivation for this orientation is to develop new kind of devices, liquid-based, which feature high level of tunability and/or new behaviour.

Short term actions for this four research directions

The first step will consist in the fabrication of elementary and large bandwidth devices to settle down generic and precise modeling. The motivation is to interlink in a reliable way liquids properties (for instance biological parameters or new modified liquids for electronics) with RF signatures. Adequate multiphysic approaches will be consequently studied.

Devices' architecture and design will be addressed to target high sensitivity whereas fluidic volumes have to be lowered. RF methodologies are then to be redefined as, on the contrary to classical ones, circuits have to be as sensitive as possible to environment variations. As far as devices' miniaturization is concerned, specific topologies will be developed to cope with large parasitics.

Dedicated multifunctional (RF+fluidic+bio) characterization test set-ups represent a key development for the activity, as sensitivity issue and multiscale capability are targeted. One set-up will be developed to push the limits in term of performances (RF, sensitivity, low long term deviation, controlled micro-environment...). A second one will exhibit high portability to confer ubiquous installation in any bio and medical labs.

As far as technological engineering is concerned, new materials, which will have to fulfill RF/fluidic and bio compatibilities, will be investigated in collaboration with chemists specialized in polymer (CIRIMAT...). On another hand, innovative processes will be studied to develop in the LAAS clean-room all the fluidic/bio interface in a good agreement with the RF requirements.

For screening applications, high density of RF sensors is required, but is limited by detectors' crosstalk. To overcome this strong bottleneck and reach higher integration level, the technological challenge will be to integrate CNT-based absorbing nanomaterials in both microfluidic and RF networks. Dedicated (including bio-compatibility) optimizations of such composites in collaboration with CIRIMAT will be carried out, taking benefit from already 4 years established partnership.

Bulk substrates-based technologies will be redefined and transposed to unconventional substrates, such as (1) flexible plastic films for bio-conformability applications, (2) paper for low cost and friendly environment requirements. The objective is to address in/ex vivo or environment survey notably. Low thermal budget/agressive processes as well as devices architecture will be established in this direction.

In an entire integrated microsystems vision, co-integration of RF sensors (or liquid-based RF tunable devices) and Integrated Circuits (ICs) will also be considered. Post-processing solutions based on both conventional and unconventional technologies are foreseen.

This approach of IC-RF sensor (or IC-RF /liquid device) microsystem corresponds to the intermediate stage toward **the long term vision** of complete RF based lab-on-a-chip, which will integrate RF sensing, RF manipulation, RF information post-processing, and RF wireless transmission, where RF signals are the common and key character.

Optoelectronics for Embedded Systems – OSE –

Permanent Staff:
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Context and Challenges

The use of embedded sensors has become widespread Our aim is to advance knowledge in the design of optoelectronic sensors as well as their micro-electronic circuits for generating and acquiring optical signals. As a consequence, for the purpose of measuring quantities and phenomena of interest, we investigate the physical limits of laser sensors, i.e. both theory and methodology of measurement, as well as the information-theoretical limits of algorithms to process data. We plan to continue exploring the laws of physics regarding, in particular, optical feedback interferometers (self-mixing) and extrinsic fibre Fabry-Pérot interferometers (EFFPI) to render their evolution from emerging to emerged technologies. Moreover, each functional element of these sensors, from the analog readout circuit to the real-time digital processing, must be specifically designed for embedded applications, notably by considering the required dissipated power, silicon area and computation time.

By joining the LAAS, we expect a cross-fertilization between the Photonics Group for combining our complementary research interests and expertises, to take up a leading position by addressing the double challenge of realizing laser systems on a chip while integrating electronics. The achievement of both targets simultaneously would lead to a significant breakthrough providing smart solutions to offer practical features for a wide range of applications (transportation, healthcare, telecommunications...).

Major research orientations and projects

Physical analysis for sensors design

Optical feedback interferometry (self-mixing)

"Physical behaviour" — Self-mixing (SM) effect occurs in a laser when part of a beam backscattered from a remote target is coupled back into the active laser cavity. This allows the laser to be used as a stand-alone micro-interferometer. All our works are based on the steady-state analysis of the Lang-Kobayashi equations describing the optical feedback in the laser cavity. The validity of this behavioural model is adequate for all our present sensing applications, i.e. displacement, vibration, distance and velocity measurements. However, a complementary approach will be to consider the active cavity, the electrical charge present in the semiconductor due to the bias current and the target as a complete system. In consequence, the SM signal can be seen as the error signal caused by the optical feedback power to regulate the optical power as a function of the bias current. By considering the laser source as an oscillator, we can ameliorate our behavioral model, still exploiting the previously adopted automatic approach with functional blocks. It is expected that this model will aid in furthering better understanding of the mechanism of feedback regime switching. Moreover, this model may also enable us to determine the minimum level of optical feedback signal which may be processed in order to improve the sensitivity of our sensors.

In addition, for moderate feedback, multiple solutions of the non linear phase equation determining the behaviour of the SM effect, i.e. multiple external-cavity modes, are available. In this case, the main issue of recovering the disappeared fringes relies on the hypothesis that the system will always converge to the closest mode corresponding to a 2π phase shift. Although this situation is likely to occur for a slowly varying phase and only a few available modes, it is much less certain in the case of high values of the coupling factor and a rapidly changing phase corresponding to a fast moving target. The system may then switch to one of the many available modes depending on the instantaneous values of the relevant parameters. For this reason we also wish to investigate the nonlinear dynamics of a semiconductor laser with optical feedback for new potential high-speed applications. This would be carried out in collaboration with laboratories specialised in this physical field (TONA, LMOPS...).

"Laser sources" — The influence of physical parameters of the laser like the Henry factor, the wavelength and the laser polarisation on the SM signal may be explored more in-depth. We plan to consider different laser sources such as the blue laser, the self-pulsating DBR laser, cleaved coupled cavity lasers, q-dot lasers, electrically pumped laser nanosources as well as lasers with external resonant grating mirrors..., to extract and modify the prominent parameters for our applications. For example, in collaboration with the Photonics group,

using nanostructured optical fibres like a resonant grating may permit to design short external cavities (~1cm) suitable for wavelength stabilized 980nm pump laser modules for erbium-doped fibre amplifiers with pulse duration around 1ns.

"Voltage-acquisition for self-mixing devices" — Our aim will be to realize acquisition of the SM signal through the amplification of the laser diode junction voltage, i.e. removing the photodiode. The junction voltage is sensitive to optical power fluctuations, and we have demonstrated recently that it allows SM signal acquisition. Nevertheless this phenomenon is hitherto incompletely described. We plan to develop a model for voltage sensing that could provide theoretical calculation of the sensitivity of the SM sensor and explore its limitation in terms of bandwidth, accuracy, etc. Such a model would impact on the design of next-generation laser diodes dedicated to SM sensing applications. Voltage-sensing is of great interest initially for laser diodes structures that do not allow integration of a photodetector on their rear facet, such as VCSELs; and, subsequently it is the necessary condition to design integrated arrays of sensors (such as applicable in 1-D or 2-D VCSEL arrays).

Homodyne and Heterodyne Interferometers

The EFFPI currently used is a passive homodyne-based sensor system in which interference signals are produced uniquely by changes to the original position of the monitored target thereby provoking a variation in the optical path length. The ensuing optical path difference is then converted into the necessary parameter of interest, in this case, the displacement of a target in motion. The sensor device is in fact a dual-cavity fibre interferometer exploiting the orthogonality of the injected fundamental mode from a laser diode to produce a pair of interference signals which are locked in quadrature by optical means. This duality nature allows both periodic and non-periodic displacements to be detected with nanometric accuracy but without the ambiguity problem associated with most fibre interferometers. Although the homodyne interferometer is easy to operate as it does not require any active modulating element, it, however, necessitates a highly stable light source with little or no optical power fluctuations when high-precision and high-resolution applications are targeted. Another potential problem associated with this sensor is the variation in the interference fringe visibility, commonly known as polarization induced signal fading, when parasitic perturbations such as strains, stresses and large temperature fluctuations intervene to modify the phase quadrature condition between the interference pair. Consequently, the interferometer suffers signal attenuation and the required measurement task may be detrimentally affected.

Hence, further work has been programmed to implement a synthetic heterodyne demodulation method into the current sensor in which frequency modulation of the laser source to result in a synthetic wavelength and a carrier phase can be used to generate a set of interference fringes corresponding to an equivalent target displacement even when the target is stationary. In addition to indicating the fibre-target separation, these fringes can also serve as a reference displacement datum from which subsequent target movement can be determined. Further, by scanning the laser wavelength at a sufficiently high frequency, drifts in the sensor system due to optical power fluctuations, thermal effects in the laser cavity as well as low-frequency variation in the polarization state of the lightwave propagating in the fibre can be compensated since these are typically slowly-varying parameters. As in all precision sensing systems, the main objective is to construct a sensor capable of high-resolution measurement with good accuracy. Thus, with the availability of a reference set of fringes, minute displacements much less than a quarter of the laser wavelength can be measured with excellent precision.

The long-term ambition is to achieve sensor array capability by integrating measurements from multiple sensor nodes positioned at various locations so as to provide sensing cover over a relatively large zone. The unique opportunity provided by our association with LAAS thus allows access to various technological platforms, in particular MEMS design and fabrication. This capability can be introduced into the fibre sensor in the form of MEMS-based micro-mirrors which can be actuated by a command device to synchronously scan a single laser source fabricated on an integrated photonic waveguide to interrogate multiple sensing fibres strategically located at selected points or sites. Subsequent detection and/or demodulation of the resulting interference signals can then proceed via the well-known time or frequency-domain techniques incorporating the phase demodulation method developed by LOSE. Finally, absolute interferometric measurement capability, the most elusive and exclusive of all interferometric techniques, using the EFFPI, will be investigated for high-performance sensing applications with a view to meeting operating requirements in the aerospace industry and, more importantly, in sustainable development as well as in risk management.

Integration of electronic functions for embedded systems

Self-mixing interferometry

"Optimisation of the analog readout circuit" —SM devices require an analog amplifier operating with high gain and a large bandwidth together with low power consumption principally for embedded systems. For this purpose, we firstly plan to develop a charge amplifier for our displacement sensor in order to reduce the power dissipation without decreasing the gain. Nevertheless, high bandwidth is required (several MHz) for Doppler velocimetry. This amplifier may be used in combination with a heterodyne technique in order to decrease the frequency range and increase the signal to noise ratio. This a key point for all potential opto-microfluidics applications. Moreover, for Doppler frequency measurements a FFT is generally used but this method is inaccurate when the signal is corrupted by speckle. We plan to adapt this method for the analog readout circuit to avoid calculating the Doppler frequency. The algorithm will first consist of driving the synchronous frequency of the local oscillator to obtain the Doppler frequency, spectrum aliasing being digitally filtered.

"Self-mixing SiP" — An upgrade of the SM micro-interferometer is the development of a System in Package (SiP) including the integrated analog / digital electronics on a CMOS chip, the signal processing and the laser diode all on a silicon platform. The final objective is the design of an embedded wireless optical micro-sensor network which is suitable for a wide range of applications like nondestructive testing for aerospace vehicles, intelligent transport systems, home care, etc. In such applications, large amounts of data may also be processed in parallel. However, performing such processing by software running on a high-performance processor or only by hardware is not efficient except for a few specific cases. We expect to develop a hardware/software partitioning approach for these SiPs by taking into account the 3 fundamental parameters: power consumption, silicon area and computation time. This methodology will be based on VHDL or VERILOG languages for facilitating the integration in comparison with C++ or SystemC languages. The obtained model will include the 3 parameters to be optimised with a heuristic method and the associated functional elements. A challenging result will be the prediction of the power consumption due to software function calls.
First, we will focus on the velocimeter designed within the laboratory before any consideration is given to generalise this method to displacement and distance sensors as their signal processing is rather complex. Once the results from our discrete laser prototype demonstrate the usefulness of the proposed methodology, a wireless sensor network consisting of spatially distributed autonomous devices based on SM micro-interferometers to cooperatively monitor physical conditions at different locations will be investigated. We will also examine the manufacturability and scalability of massively-parallel monolithic laser-array system, taking into account the effect of optical crosstalk between the channels.

Moreover, we will also explore the interest of coupling high-speed adaptive optics to SM sensors. As a matter of fact, mis-focusing of the beam will modify the feedback in the laser cavity and consequently limit the dynamics of the sensing range. A first step will be to validate how adaptive optical techniques may improve performances of SM sensors. For the purpose of designing a SM SiP, the final adaptive optics will have to be integrated in the future micro-system. The on-going research project of the Photonics Group on the fabrication of microlenses using a low-cost polymer dispensing technique based on the use of a silicon micro-cantilever robotised spotter system may lead to the design of the required adaptive micro-optics.

Implantation of new data processing techniques
Analog integrated Neural networks (NN) have been implemented to perform classification and detection as well as linearisation of physical phenomena. For example, we have designed such a NN for real-time non-destructive testing with a laser range finder. It will be interesting to implement others data processing techniques (like turbo decoders) in ASICs - using CMOS analog multipliers, adders and non-linear functions or in FPGAs - in order to compare the performances obtained in terms of precision, speed, adaptability and easiness of integration. Our purpose will be to develop generic structures notably for laser embedded sensors.

Photonic integrated & embedded sensors

Non-destructive testing
"Civil engineering" — Considering sustainable development and the preservation of heritage buildings, it is nowadays necessary to monitor the status of ageing civil engineering structures, including concrete. In fact, degradation of this material may be accelerated by various environmental factors (carbon dioxide, pollution ...). For maintenance or repair, the use of diagnostic tools is becoming increasingly necessary. This specific continuous monitoring is based on non-destructive inspection liabilities whose purpose is to analyse the information emitted spontaneously by structural deformation, vibration, acoustic emission,

temperature, moisture… We plan to exploit our SM displacement sensor from weak to strong feedback regimes with a monitoring methodology that will be based on vibration analysis of structures using different approaches: modal analysis, chaos, stochastic processes. It will permit to identify the loss of mechanical integrity through changes in the dynamic behavior observable on a global scale of the structure under surveillance. Moreover, a sensor network will be required to simultaneously collect multiple points of measurements. This project will be conducted in collaboration with the Laboratoire Matériaux et Durabilité des Constructions.

"NDT for aeronautical applications" — Our aim is the full-field characterization of advanced composites from the manufacturing stage through the mechanical testing cycles to optimise the production procedure and to forecast the final performance of these next-generation materials. The detection of damages within composite structures due to impacts (cracks, fractures) and during their normal operating cycle will also be a priority. For this purpose, a FBG (fibre Bragg grating)-based sensor has been designed. Quasi-static strain detection will be explored with the SM demodulation technique by the introduction of a heterodyne detection scheme in which the interrogating light source (typically a DBR laser diode) will be frequency-modulated in order to improve the strain sensitivity of the FBG device when the induced strain varies very slowly over time. Another feature will be the possibility of interrogating multiple FBGs provided the modulating frequency is high in comparison with the variation in the measured parameter. Furthermore, advantages of this sensor and of the EFFPI for axial measurements will be combined for structural health monitoring. The in-situ cure monitoring and post-cure monitoring of advanced fibre-reinforced composite materials with both sensors will be explored in collaboration with the Institute of Materials Research and Engineering of Singapore.

Another project envisioned is the optimisation of high-speed machining for milling titanium. As a matter of fact, a small increase in cutting speed can lead to a big increase in edge wear. Additionally, because of the metal's low thermal conductivity, overly aggressive milling may even incur a risk of combustion. Although the speed of production can still be increased, it requires tooling that can compensate for any shortcoming the machine may have. Consequently, we will improve our SM behavioural model in order to take into account the influence of speckle. This will be carried out by considering a new coupling factor varying with a reflection coefficient of the target considered as a 2D low-pass Gaussian random complex variable which depends on the time-varying position of the impact point and on the roughness of the target surface. It may lead to the possibility of quantifying the effectiveness of the milling as a function of the machined surface roughness. A real-time SM sensor coupled with neural networks may then be designed for simultaneous vibration measurements and classification of roughness. A 3-axis linear MEMS accelerometer may be added on this laser system in order to remove environmental vibrations. This should result in a highly versatile and useful tool to benefit high-speed machining processing and its stringent mechanical requirements.

Note that, we are in the process of negotiating with the NDT service of Airbus the possibility of being a tandem partner as a recognition of our expertise.

Medical applications of self-mixing effect

Optical sensing devices in medical applications present several objects of interest. It is a non invasive sensing method, so pain or discomfort can be reduced. It is not affected by high level electromagnetic fields, so it will work in hostile EM environments. In the case of SM sensors, dimensions of micro-electronic devices and the long range operating distance could make it a very discrete device which would not be rejected by the patients for everyday home care. Over the next few years, we will develop SM sensors for several applications in the medical field. Among them, blood flow measurement on skin vessels for early cancer detection and heart monitoring during the MRI process are the most expected. The velocity sensor that will result from optical feedback in VCSEL arrays shall be able to process parallel measurement of skin vessel blood flow. With such integrated array of sensors, the device will perform fast scans of important skin surface. Low production cost and low power consumption of VCSELs will allow affordable and embedded wireless devices. Both SM displacement and velocity sensing can be used to monitor heart beat during MRI where traditional ECG is inefficient because of strong electromagnetic fields. Our partners will be the Univ. of Queensland and the Princess Alexandra Hospital, with a support of the Australian Research Council. Other biomedical applications of the SM effect may be investigated such as monitoring diabetes, hypertension (high blood pressure), MMG (mechanomyogram, i.e. human muscle-vibration measurement), cochlear vibrations… Moreover, our SM laser sensor may permit to monitor locally flow velocity in microchannels for blood microcirculation as well as in microfluidic devices for chemical processing for example. The self-aligned focusing cone developed by the Photonics Group may be helpful when measuring local velocities at distances around 10µm.

Sustainable development

"Improvement of power-generating windmill efficiency" — Windmill turbines are one of the major options to fight against global warning and for sustainable development. To increase the energy production, a real-time estimation of the wind velocity is required. The measurement needs to be performed at a reasonable distance from the windmill that can produce air flow perturbations. A partnership with a start-up SOM Systems is under negotiation. The long-term project is to develop a SMI velocimeter which is able to determine the direction of the wind by focusing on particles presenting diameters from 0.1 to 5µm, so the device could be installed on each windmill, when only one measurement for a field of windmill is actually processed.

"Submarine Lab-on-Chip" — The MAISOE project (2009-2012) is funded by the RTRA STAE and involves local laboratories: LCA / CIRIMAT / LAAS / LGC / LMTG. It is devoted to the development of new in-situ hydrogen and methane sensors, which will provide unique and innovative insights into the potential of hydrothermal systems as an inexhaustible energy supply and the geochemical cycle relating hydrothermal fluid generation to marine biology. In collaboration with the Photonics Group, we propose to demonstrate the feasibility of an optical fibre sensor for the detection of submarine dissolved methane. The sensing part of the device may be based on polymer combined with crytophane, a methane-sensitive absorbent, so wavelengths of 1.3 µm and 1.6 µm would permit differential detection of trace quantities of the targeted gas. The target performance of the sensor for refractive index sensitivity is of the order of 10^{-5} to 10^{-6}, corresponding to tens of nano-mole to nano-mole in methane concentration.

"Submarine seismic wave détection" — as a sequel to the on-going LINES project (Laser INterferometry for Earth Strain, funded under the framework of the ANR Natural Risks program), a submarine installation of our EFFPI will be considered for seismicity monitoring. The feasibility of an Ocean Bottom Seismometer (OBS) will be carried out in order to assess the operation of the whole system as well as the installation procedure. In particular, fault segments in Guadeloupe are intermittently activated by short-lived shallow earthquake swarms with hundreds of events, the origins of which remain hitherto unknown. For accurately locating, understanding, and monitoring this very unusual seismicity, it is necessary to have real-time information from an offshore optical fibre sensor system, 8-10 km long, incorporating optical fibre seismometers, and an optical pressure gauge (especially for tsunamis detection), all instruments being based on the EFFPI. Another site to consider will be the Corinth rift, a European pilot site strongly supported by the EC and the French CNRS/INSU, for the study of fault mechanics and seismogenesis. Its micro-seismicity has hypocenters 5 to 10 km in depth under the gulf. For improving the relative vertical location of these hypocenters, and obtaining reliable geometries for the related activated faults, it is requested to have permanent OBS, in complement to seismic arrays on land. A 10 km long fibre will be installed offshore, with optical fibre seismometers and an accompanying fibre pressure gauge. The marine installation will be performed in collaboration with HCMR and the University of Patras. The challenge will be to perform during years high-accuracy measurements of micro-displacements with a 10 km-long fibre-optic remote sensor.

"Storage of carbon dioxide" — Our interferometers (EFFPI and SM) may also be used for monitoring CO_2 underground storage. Our instruments are expected to be tested at the Izaute storage site (TOTAL gaz storage field). The implicated sensors thus belong to the portfolio of techniques necessary for risk assessment and control in underground gas storage facilities and operations. They help secure the seals and gaskets from mechanical damage, hence ensuring containment in case of leaks or emergencies.

Space applications

Radiation-hard instrumentation of spatial sensors

Concerning the CASA project (CApteurs Spatiaux pour l'Astrophysique, 2008-11) funded by the RTRA STAE, we plan to realize multi-sensors heads for IR and X, γ astronomy and for the spectrometry of particles in the solar system. These multi-sensors heads will be instrumented in low noise, low power radiation-hard analog-digital ASICs. We wish to accumulate specialist know-how and to transform the on-going 3-years effort into a stable structure allowing the design of devices for space missions by regrouping the expertise of CESR, AIME, ONERA, with academic and industrial support.

Research domain
Modeling, Optimization and Control of Systems – MOCOSY –

The research federated by the MOCOSY area is driven by today's scientific challenges and the vision of the technological evolutions to take place in the next decade. Among the important challenges, we can mention the following:

- Understanding and controlling highly complex dynamics;
- Controlling large interacting dynamical systems such as power, communication, and transport networks, but also biological regulatory networks;
- Guaranteeing safety and achievements of controlled systems in uncertain environments;
- Integrating new technologies like "drive-by-wire", wireless communications, nano-sensors and actuators, etc. in controlled systems.

These challenges lead us to articulate our perspective around three key topics: uncertainty and robustness, distributed and cooperative systems and optimization.

Uncertainty and robustness impact the modeling formalisms and the algorithms implementing the tasks of interest. These must cope with incomplete and imprecise knowledge as well as the occurrence of faults and different kinds of disturbances. Stochastic models, polytopic and norm-bounded uncertainty models, set-membership formalisms, and logic and constraint-based models are our tools of choice. The problems of delivering stability and performance certificates, analyzing the conditions for diagnosability and self-healabilty, and guaranteeing adaptivity to non nominal situations through fault management and flexibility will be addressed.

Distributed and cooperative systems define a set of new problems and call for the adaptation of our methods. In our focus of interest are situation assessment based on smart distributed systems, networked systems control and diagnosis, and negotiation in networks of decision centers.

Optimization is the cornerstone of all our solutions. One challenge is to compromise between optimality and robustness. Embedded optimization for autonomous systems, involving reconfiguration and recalibration of control laws particularly designed for energy management and safety improvement will be given special attention. New methods from matheuristics for multiobjective integer programs will be investigated as well as discrete optimisation methods for robust scheduling.

Let us mention on-going discussions with the LATTIS Laboratory that lead us to foresee launching a new research group, including 6 permanent researchers. The research topics concern the analysis of non linear systems modeled by maps, including bifurcation studies and complex behavior understanding, focusing more particularly on chaotic behaviors. Applications are found with non linear circuits, evolution systems, and transmission systems.

Diagnosis and Supervisory Control – DISCO –

Context and challenges

The analysis of the impact of faults on a system occurs throughout the entire life cycle of a system. In the last few years, there has been a significant trend for accounting for fault analysis and diagnosis requirements in the solutions produced for tasks such as design, failure-mode-and-effects analysis, sensor placement, end-of-line testing, monitoring, on-board fault detection and recovery, testing for diagnosis, maintenance, repair and treatment planning. Diagnosis is hence not considered any more in its initial *stricto sensus* version aiming at on-line or off-line fault detection, isolation and identification.

At the design stage, this results into an important research track concerned with properties related to diagnosis. Besides, diagnosis is now regarded as part of entire fault management architectures. For autonomous systems, it positions itself in cooperation with reconfiguration and planning so as to jointly solve the state tracking/decision problem. In domains in which faults are accounted for through maintenance programs, it appears as an ingredient for achieving condition monitoring and maintenance.

In this context, our mainstream research in model-based diagnosis has a key part to play. Models are indeed the basis for providing a representation of the underlying knowledge that permits a reuse for the various tasks and an integrated perspective.

On the other hand, networked systems being more and more common, distributed aspects and cooperation turn essential. Sensoring capabilities become ubiquitous, but far from eliminating the diagnosis problem, this shifts the problem towards considering highly reconfigurable systems that evolve across time. These topics, that strongly relate to the LAAS ADREAM program, translate into new challenges for diagnosis and supervision.

As a consequence of these new trends, the two diagnosis communities both in the Control field and the AI field, in which the DISCO group is well established and recognized, remain very active.

From the application point of view, the DISCO group research activities benefit from a rich industrial environment concretized by the *Pôle de Compétitivité Aerospace Valley* and its Federated Program on diagnosis. The numerous industrial solicitations for collaborative projects are as many opportunities for DISCO and show that the needs for diagnosis are real. Nevertheless, ne of the resulting weaknesses is the dependence on industrial data to test our methods. The experimentation platform of the internal program ADREAM is hence seen as a good opportunity.

The other application mainstream of DISCO finds echo in the second regional *Pôle de Compétitivité Cancer et Biosanté* and in the LAAS Program "*Interactions with life sciences*". Bio matter analysis and ultimately medical diagnosis linked to target therapies open new challenges for our machine learning based methods, including appropriate data pretreatment and selection of the most relevant dimensions.

The DISCO group conducts a rich and varied methodological research, which puts it in the appropriate position to approach the scope of diagnosis applications found in industry as well as in the health domain. Formalisms taken from Artificial Intelligence naturally connect with continuous and discrete models from the Control community, as well as with machine learning and classification techniques. This large spectrum of expertise and multidisciplinary approach are the trademarks of the group.

Let us notice that the DISCO group is at the moment one of the largest research group in Europe dealing with diagnosis and related research topics.

Major research orientations and projects

Model based diagnosis

Model based diagnosis remains a major track for our future work. Section 1 presents several lines that focus on diagnosis algorithms, whereas model-based diagnosis in relation with other tasks involved in fault management architectures is the focus of section 4.

Distributed diagnosis in cooperative contexts and networked systems

Distributed architectures become the standard in many domains, and it is important to design diagnosis systems in such framework. Diagnosis then relies on a set of local diagnosers that elaborate local diagnoses. Global diagnoses are obtained either in a so-called decentralized way, by centralizing the local diagnoses in a supervisor or in a so-called distributed way, through communication among the local diagnosers. In this context, DISCO aims at developing generic health monitoring architectures, robust to reconfiguration, providing an accurate diagnosis at both local and cooperative levels.
In this context, perspectives emerge for diagnosis in communication and service oriented systems related to non functional properties like QoS. In these

domains, decisions are generally taken based on a symptomatic analysis, which does not infer back to the real causes of the problems, often leading to unsuccessful or irrelevant actions. Based on our experience of the WS-Diamond Project, we believe that diagnosis driven adaptivity is a research to continue. Some issues of interest, which are foreseen to be approached in collaboration with the LAAS-OLC Group, are:

- Cooperative diagnosis between transport and application levels when faults may have an impact at different levels of the network and on the supported applications.
- Diagnosis for cooperative QoS management considering different types of faults, in particular exogenous faults, e.g. non anticipated high traffic flows, to which QoS is related
- Diagnosability and signaling protocols, mobility and dynamic topology introducing the need to question monitoring data integrity.

The current ROSACE project (http://www.laas.fr/~khalil/page/index.php?n=PROJETS.ROSACE) as well as the LAAS ADREAM program provide general frameworks to approach the above issues. Designing, specifying, implementing and deploying a set of mobile autonomous communicating and cooperating systems with well-established properties (safety, self-healability, and self-adaptation in a dynamic environment) are indeed the targeted goals.

Adaptive model-based diagnosis systems

Model-based diagnosis is a white box method, i.e. it requires the knowledge of a correct and complete abstraction of the underlying system. For systems that operate on a very long term, the system may evolve at operating time (new operating requirements, new safety constraints, new diagnostic objectives, etc) and the diagnosis system must take these evolutions into account. The incremental construction of the diagnosis system thus relies on model upgrades and appears to be an efficient solution especially for complex component-based systems. The cost of diagnosis upgrade is then minimized and the diagnosis model can be used to validate each modification. It may also happen that the knowledge about new components is not available (black-box) but the diagnostic architecture must go on performing consistent diagnosis.
In this case, diagnosis is performed on a 'grey box' system and must combine model-based techniques with data-based techniques like knowledge discovery or machine learning techniques, which is one of our lines for future works within the AIRSYS Join Laboratory in collaboration with AIRBUS.

Filters and observers for on line detection and diagnosis of continuous systems

Numerical properties — This research line itemizes along two main directions. First, DISCO aims at developing new approaches for state estimation in a bounded error context using set-membership methods. At the moment we are testing a low complexity approach based on the use of the mean value and intermediate value theorems, thus requiring some local monotonicity conditions. We plan to apply the method to the on-line detection of oscillatory failure cases in flight control systems. This work is done within the SIRASAS project (https://extranet.ims-bordeaux.fr/External/SIRASAS/) that aims at increasing autonomy and operational efficiency of civil aircrafts and satellites.

Second, we plan to consolidate our work on non linear observer-based diagnosis. The idea is to build upon a previously developed method for monitoring sensor and actuator faults that isolates the faults faster than traditional methods. The problem that remains is the one of discriminating between faults and disturbances, which are both of additive type. Using this approach for on-line detection and diagnosis would also require to increase the convergence speed of the observers.

Differential operators — Dynamic systems cannot always be approximated adequately by linear models, especially when fault detection is involved. But many physical systems present the differential flatness property which has been already used to design new non linear control laws in the field of flight control. Differential flatness implies also interesting observability properties. Then, starting from this property, we developed new state observation devices for fault detection purposes with applications to real time fault detection on very light flying devices (cf. section 1 of the DISCO activity report). We plan to fully validate our method and to investigate how to go further fault detection. As a matter of fact, the proposed approach points out towards solutions for fault identification, and we believe that a detailed analysis of the timing of the fault test propagation should provide enough information about the roots of the current faulty behaviour.

Fault class characterization — Non linear observers will also be investigated to achieve Fault Class Isolation (FCI). The problem is that for fault isolation in closed-loop systems, it is often necessary to first make a decision on which class of fault has occurred. Such a decision requires isolating the occurred fault class amongst different possible fault classes, which is referred as the Fault Class Isolation (FCI) problem. In our case, we are interested in three classes:

actuator faults, sensor faults, and process component faults. Our future work will propose possible approaches based on unknown input observers to achieve the isolation between actuator and sensor fault classes for non linear systems with unknown inputs.

Set-membership optimal input design for uncertain model identification

Parameter estimation is one of the key FDI methods. Its advantage is that it allows one to detect faults and obtain their identification as a by-product. But to be efficient, parameter estimation may require the system to be submitted to specific input patterns. Selecting these input patterns is just the goal of optimal input design.
A lot of literature is devoted to optimal input design in industrial systems in a stochastic framework. In order to obtain the optimal input and consequently the most accurate estimates of model —possibly faulty— parameters, the information contained in the system response during the test must be maximized. The information contained in the response is embodied in the Fisher information matrix. Indeed, as the measurement noise is often assumed white Gaussian with zero mean and known covariance matrix, the Fisher information matrix elements are combinations of partial derivatives of the system response variables with respect to the model parameters. Our research goal is to cast the problem of optimal input design into a set-membership approach, considering that perturbations and noises are assumed bounded but otherwise unknown.
As a corollary, we want to define identifiability in such framework and to provide a characterization and the conditions allowing us to check this property.

Diagnosis and supervision based on machine learning methods

Within the next 5 years, several axes will guide our researches concerning classification and machine learning based techniques and adaptation of these methods to new application domains, in particular in the diagnosis/prognostic of cancer.

Scalability in classification approaches for diagnosis

In most of real size diagnosis problems, the information given by the measured data is partly corrupted with uncertainty and imprecision. The classification based diagnosis methods require to consider the possible presence of uncertain or imprecise input data attributes or descriptors, as well as redundancies and/or spurious measurements. Imprecise data often appears modelised by intervals. In a starting work, our purpose is to process the interval type of data together with classical quantitative or qualitative data by means of the elaboration of partition indexes that enable the consideration of interval type attributes in the classification.
A complementary line of research is concerned with a methodology for the selection of pertinent descriptors. The only requisite of the foreseen approach is that the previous classification procedure calculates the contribution of each element attribute to its assignment to each class. By this approach, the selection of the most relevant attributes is transformed into a constrained optimization problem that, for many classification algorithms, accepts an explicit solution. Both results are applied in the medical domain for diagnosis/prognosis and therapy purposes.

Data analysis and bayesian models

Classification methods alone are sometimes not sufficient to explain the links or the complex relations between the measured values of the descriptors and the diagnosis result. There is a real need to develop a way to introduce expert knowledge into the information given by a classifier. We intend to do this through Bayesian Networks that would map both classification results and expert knowledge, the initial classification yielding the initial Bayesian Network architecture and an initial computation of the probabilities of the connections.

Properties and diagnosis-oriented design

The main track of work referring to properties related to diagnosis is concerned with diagnosability of DES. Our challenge is to redefine the diagnosability problem in a way that handles the time aspects of the system behaviour. These may be essential for the discrimination of some faults. Considering time aspects, through dates, durations and delays, supposes to have a finite representation of a possibly infinite space. For this study, our tools of choice are timed petri nets and chronicles.
Other extensions of diagnosability are also envisioned, in particular the recent work that casts diagnosability at the level of properties for state-based systems needs a counterpart in the discrete event systems framework.
The analysis of diagnosability in distributed environments is also the focus of future developments. In this context, there is no global view of the problem: each sub-system has local knowledge and communicates with other subsystems for refining its knowledge.

Fault management architectures

This section presents several lines of work that aim at integrating diagnosis in fault tolerant architectures or

therapy oriented solutions, hence relating diagnosis to other tasks.

Diagnosis, active diagnosis and planning for autonomous systems

At the core of autonomy lies the articulation of planning as decision making, and diagnosis, a generic form of health monitoring. Planning generates a control program, also known as a plan, which describes the sequence of actions necessary to achieve some predefined goals. Diagnosis offers the capability to detect, isolate and sometimes identify defects or more generally the root causes of one or more discrepancies, in models, plans or reasoning. In the last two decades, most architectures for autonomy have derived from an adhoc and empirical partition of the agent and its world in their representations and operations. This partitioning leads to a set of modules, typically a planner/scheduler, a health monitoring system, and an executive.
This research direction aims at justifying the use of diagnosis when it is needed, and at articulating its presence with other functional modules within a generic architecture for autonomy, which represents the cornerstone to achieve the truly robust autonomy of tomorrow.

Diagnosis and control law reconfiguration

The work already done on this topic has resulted in a method for the analysis of the reconfigurability of a controlled system when a fault occurs. Our current objective is to put the algorithm on line in order to conclude on system reconfigurability in real time and either calculate new trajectories and the appropriate control laws or make other decisions in order to guarantee the stability of the system and to keep the state of the system close to the desired state.
On the other hand, we plan to study how a hierarchical diagnosis may be interesting, specially at the functional level, in order to reconfigure a system in terms of functions. In all this work, the health monitoring system, including the diagnosis process, has to be robust to those reconfigurations.

Diagnosis and design

One main difficulty of model-based diagnosis is the definition/acquisition of the diagnostic model of the system. To determine such model, we need to strengthen the links between the models used for the design of the system and the models for diagnosis and account for diagnosis requirements during the system design phase.
The ISAURICA project, in which we are involved, aims at linking physical and functional models that are available at design time to build a model of the system able to discriminate a set of anticipated faults according to the available observations. Moreover, we want to take the system ageing into account in the evolution of our models in order to diagnose fault parameter deviation. Another way to strengthen the links between the design of the system and its diagnostic model is to analyse diagnostic properties (accuracy, discriminability, diagnosability and its extensions) based on a current specification of the system and provide design feedbacks to improve the diagnostic capabilities by adding sensors on the implemented system with a minimal cost.

Diagnosis and prognosis

Prognosis is of great interest for industrial applications and especially for preventive maintenance. Diagnosis and prognosis are closely related: *diagnosis* determines the set of faulty configurations that are consistent with a given set of observations whereas *prognosis* determines a faulty configuration that will be reached in the future and that is consistent with the actual diagnosis and with the ageing model of the system. We have already started some work on this topic (cf. section 4 of the DISCO activity report). Nevertheless, more work is needed in this field in order to better understand and benefit of the relationships between diagnosis and prognosis. Among the issues of interest are the characterizing the two tasks in a logical framework, studying prognosis methods relying on reliability concepts, proposing a definition of prognosability, etc.

Diagnosis and therapy

Within the next 5 years, the main developments along classification based techniques and results for sensor placement will be adapted to the medicine domain, more particularly to cancer diagnosis and clinical treatment adjustment (within the project Oncomate). Our objective is to develop a methodology coupling different methods such as classification, Bayesian networks, inductive logic to improve cancer diagnosis and prognostic. Future developments will first of all rely on coupling clinical data bases containing information coming from the analyzed tumors (size, shape, radius, grade, progesterone or estrogens receptivity, growth factor receptors titrations, cells anatomy) with patient information (age, possible genetic predispositions, health history) and biochips analysis (dosage of proteins, gene analysis). We also wish to highlight the link between the patient data, the type of cancer, the received treatment (radio or chemotherapy, adjuvant therapies) and the outcome of the disease (recovery, relapse at 5 or 10 years or definitive progression).

It is foreseen that the analysis of such type of data will exhibit new problems. In particular, the analysis of high amounts of data (from 1500 for a typical protein biochip analysis to 50 000 for a gene profile), when very few may make the difference between the sub-types of cancer and so will influence the treatment seems difficult. Appropriate data pretreatment and/or the selection of the most pertinent information is hence crucial. This is to be linked to the sensor placement problem. On the other hand, biochip analysis yields a lot of data revealing uncertainty or imprecision. In parallel, classical clinical data bases include data such as "the cancer grade", which cannot be seen as pure quantitative or pure qualitative information. Finally, classification alone is not sufficient to explain the links patient/treatment/disease outcome and help doctors to personalize the treatment for each patient (target therapies for cancer sub-types). So we need to couple expert knowledge to the information given by the classifier.

For the two problem mentioned above, the line of work presented in section 2, i.e. on one hand data type valuated by an interval, and on the other hand mapping Bayesian networks and/or inductive logic to expert knowledge, seems relevant.

Universal diagnostic architectures

Nowadays, systems are not only the assembling of components with heterogeneous nature (discrete, continuous, hybrid) but they are also highly reconfigurable in the sense that the topology of the system is not fixed (see the ADREAM project). From a diagnostic point of view, it is then required to set up universal and open diagnostic architectures (like service oriented architectures) that are robust to reconfigurations (add/removal of components on-line). The main challenge is to always guarantee the global consistency of the diagnostic process by automatically updating the deployment of the architecture after a reconfiguration. The definition of such architectures requires generic diagnostic description languages (model type, diagnostic objectives, diagnosability degree,…) that will ensure the interoperability, the consistency and a diagnosability degree of the deployed diagnostic modules at a given time.

New collaborative projects and valorization

Type of project	Acronym: Title — Partner(s) — Website	Period
FRAE	SIRASAS: Stratégies Innovantes et Robustes pour l'Autonomie des Systèmes Aéronautiques et Spatiaux — IMS, SATIE, CRAN, LRI, ONERA, CNES, Thalès Alenia Space, AIRBUS — https://extranet.ims-bordeaux.fr/External/SIRASAS/	2007-2010
CNRS/JST ICT	Knowledge-based Discovery in Systems Biology — NII Tokyo (2006-2009) within the Japanese-French Laboratory for Informatics (LIA JFLI) http://www.springerlink.com/content/7035238v7p544534/	2008-2012
PREDIT	DIAPA: Diagnostic Automobile par Apprentissage — LAAS-N2IS, HEUDIASYC-CNRS, PSA Peugeot Citroën, Delphi, Freescale, Serma Ingénierie — http://www2.hds.utc.fr/index.php?id=243	2007-2010
CNES	AGATA: Etudes et architectures pour l'autonomie et le diagnostic — CNES, ONERA — http://agata.cnes.fr	2005-2010
OSEO-ISI	AMIC-TCP: Architecture Multiplexage Informatique Communication - Transport en Commun de Personnes — ACTIA Sodielec, ASSCOT, ATON Systèmes, Citilog, LAAS-OLC, IRIT, TISSEO, Trialog	Submitted
FUI-AAP8	ISAURICA — Rapid Decision Making at Architect Level Combining Model Generation (ISAURE) and System Modeling (Modelica) — ACTIA, LMS Imagine, Continental, Labinal, Messier Dowty, Snecma Propulsion Solide, DIGITEO/Scilab, INSA Lyon, INSA Toulouse (LATTIS and ICA), INRIA, Université de Pau (LIUPPA)	Submitted
Pôle CANCER-BIO-SANTE	INPAC — Pierre Fabre, BOOSTEC, LGC, LAAS-MIS — http://www.minefe.gouv.fr/presse/communiques/2008-02-25_resultats_5e_AAP_annexes.pdf	2007-2010
CNRS/ACFR	DATOR: Diagnosis Applied to Outdoor Robotics — ACFR	2009-2010
DGA/EADS	DOPEC: Démonstrateur pour l'OPtimisation de l'Emploi des systèmes Capteurs — EADS Defense & security, LORIA	2009-2011
CNES	Diagnostic Réparti pour Satellites Autonomes — CNES	2009-2012
NICTA/CNRS	PICS NICTA/CNRS	Processed
InNaBioSanté	ONCOMATE: Olfactive Nano-detection of Cancers Obtained from Machine-learning TEchnology — IMRCP, PTFB, Institut Claudius Regaud, LAAS-NANO, INNOPYS — http://www.innabiosante.fr/ONCOMATE.html	2008-2010
RTRA STAE	ROSACE: RObots et Systèmes Auto-adaptatifs Communiquants Embarqués (RObots and self-adaptive Embedded Communicating Systems) — ONERA, IRIT — http://www.irit.fr/Rosace,737	2008-2012
PCP	Supervision dans les environnements organisationnels distribués — Universidade de Los Andes, Venezuela	Submitted

Modeling and control of Networks and Signals – MRS –

Context and Challenges

The success of the Internet — well beyond the initial expectations of its inceptors — has resulted over time in its extensive usage for societal and economical reasons. The Internet is today the fundamental component of the worldwide communication infrastructure playing a crucial role in our society. As the main enabler of our information era, the Internet plays a critical role in education, entertainment, business, and social life.

The success of the Internet is yet to be amplified in the near future, thanks to three major on-going evolutions. The first one is the progressive transformation of the Internet towards a global communication infrastructure supporting a large variety of multimedia services with stringent quality of service requirements in addition to traditional document-retrieval applications. The second one concerns the trend towards seamless connectivity between fixed and wireless networks that will allow users to access the same services, no matter what their locations or devices. Finally, the third one is the rapid development of the SaaS (Software as a Service) concept, where a software application is hosted as a service provided to customers across the Internet.

As more users join this global network (from developing countries, for example) and applications become bandwidth-hungry (video on demand, for example), the pressure on the available bandwidth will only increase. In this context, one of the major challenges facing this global communications infrastructure is the efficient utilisation of the available resources in order to provide a high level of quality-of –service to its users.

Some of our major research directions are oriented towards this challenge of designing network algorithms for efficient resource utilisation in communication networks. These directions concern improvements not only for the end-users but also for the network operators.

Concerning the dynamic systems activities (modelling, identification, filtering, realization theory), the future development of embedded and distributed systems is a real challenge that will be backuped by the ADREAM project. It will concern, for example, navigation issues of people outdoor or in buildings, communications, multi sensorial merging (GPS, UWB, vision, MEMS...), robotic, aeronautic and Defense applications...

Strength: Diversity of research fields (from signal to network); 8/10 full-time researchers (CNRS); pioneering methodology contribution (networks hybrid simulation, IIR Volterra filtering, hereditary algorithms, diffusive representation); close collaborations with industry; PhD students find jobs quickly; good material environment.

Weakness: lack of recent recruitment and low international recognitions for dynamic systems activities.

Opportunities: proximity with many universities and engineering schools; some activities close to the ADREAM project; research fields of high worldwide priority.

Threats: lack of PhD candidates; threat on the CNRS future; difficulties to obtain funding for fundamental research.

Major research orientations and projects

Intelligent-router based network protocol design

The current generation of algorithms were designed to operate in networks with very little built-in functionality. For example, one of the key algorithms, called TCP, which controls the congestion on the Internet, was designed in late 1980s when access speeds were of the order of kilobits per seconds. Even though this algorithm has proved to be robust until now, it is now known that this algorithm will be inefficient in a network of the size and the scale of the future Internet. One of the main reasons for this is the fact that it was designed to operate with very little information on the state of the network. This design principle will be a serious handicap in the future when networks will be more dynamic and users will be more demanding in terms of quality of service. However, with the growth of processing power available in the chips, we believe that is now time to revisit this philosophy. Indeed, the routers in a network are in an excellent position to help design efficient bandwidth-sharing algorithms and dynamic routing strategies because they have first-hand information on what happens inside the network. Thus we believe that the role of routers in the next generation networks will be much more prominent. This clearly calls for a complete rethink of the design principles for resource allocation algorithms in the Internet.

The main goal of this research direction will be to develop analytical tools to study the fundamental role that routers can have in the design of dynamic resource allocation strategies. Such dynamic

strategies will improve the ability of IP networks to dynamically react to traffic and topology changes. Progresses in network auto-adaptivity will not only result in a better quality of service perceived by users and in an improved resource utilization, but also in a more progressive network planning, leading to reduced costs.

In this research program we aim to:

- Revisit the design principles behind the currently implemented resource allocation algorithms in the Internet, and explore their limits. We believe efficient and robust resource allocation will be critical in the data networks of the future, and this can be done more efficiently by
- Propose routing and congestion control algorithms that are dynamic, more responsive to network conditions, and that are adapted to the networks of the future.

Game theory based resource allocation in wireless networks

Wireless ad-hoc networks are gaining in importance not only because they allow mobility for the users but also for the ease with which they can be deployed in urban and rural areas without the need to lay cables. Since bandwidth is a much more costly resource in wireless networks, it is important to design algorithms which permit efficient allocation of bandwidth to users. However, unlike in wireline networks, the bandwidth available to a user depends upon the interference due to the transmission of the other users in the network, proximity to the base station, and also the energy available to the device. In ad-hoc networks with minimal infrastructure, the resource allocation algorithms are completely decentralised, i.e., mobile devices take the decision based on their interference, the signal strength and their energy levels. It is known that when users make selfish decisions, the resource allocation is generally worse off than when decisions are made centrally by the base station. However, making all the decisions centrally becomes computationally complex for the base station when the size of the network becomes large.

In this research direction, we intend to study methods of improving the efficiency of resource allocation strategies while maintaining the decentralized approach. A particularly promising approach we will investigate is the so-called Stackelberg games. In a Stackelberg game there is a mixture of "selfishly controlled" and "centrally controlled" users. The decision of the centrally controlled users will influence the subsequent actions by selfish users. This mechanism can greatly help reduce the degradation in system performance due to selfish behaviour. We will use an extra intelligence at the base station for improving the efficiency of the equilibrium and we will allow the participation of the base station in the game. The base station may participate by broadcasting common messages to introduce hierarchy between mobiles: leaders and followers.

The study of "Price of Anarchy" provides a relevant framework to compare the performance of algorithms and choose the most suitable one. Our aim is to design such a theoretical framework that will enable to choose the most suitable algorithm for implementation.

In the same spirit as the Price of Anarchy, we intend to derive bounds on the transient behaviour of the algorithms. Such bounds are useful especially for dynamic systems in which a change in system parameters requires the algorithm to converge to a different equilibrium point.

Robust Network Optimization

With the Internet getting more and more present in our daily activities, network outages or even significant degradations of the quality of service become less and less tolerable. To avoid network congestions and the resulting service degradations, Internet Service Providers (ISP) need to properly dimension the core network and trunk lines giving the subscribers access to the Internet. A cost-efficient alternative to installing excessive amounts of capacity is to use traffic engineering techniques.

However, common approaches for traffic engineering assume that the traffic load in the network is known or can be measured. Relying on precise knowledge of the traffic matrix enables nice provably optimal solutions. However it is unrealistic because, in practice, traffic demands between nodes change continuously. With the increasing popularity of higher bandwidth applications, traffic patterns are more volatile even in the aggregate. This is a major obstacle to the use of traditional traffic engineering techniques.

Taking into account traffic uncertainty and searching for robust solutions to network planning problems is a major challenge for next generation networks. This is a very recent and dynamic research area. We will participate to this dynamic in cooperation with the team of Bernard Fortz at Université Libre de Bruxelles within the framework of a PHC Tournesol project.

A first work will deal with the analysis of the information available to the network planner in order to reduce the uncertainty sets as much as possible. We will then study several robust network planning problems. One of these problems concerns the minimization of bandwidth reservation for the VPN

design problem in the case of single path routing. We plan to study an exact approach as well as several heuristic schemes (local search methods, Lagrangian relaxation). The robust optimization of IGP weights will also be studied using local search methods. Finally, we will study the capacity-planning problem in the case of modular capacities assuming that the traffic uncertainty set is an ellipsoid.

Internet Traffic Modelling

A considerable research effort has been devoted to the development of an Internet teletraffic theory in the last decade. In contrast with its counterpart for circuit-switched networks, this theory is still in its infancy, although significant progress have been made in recent years. The main difficulty here comes from the elastic nature of most Internet traffics whose throughputs are modulated by the TCP protocol depending on traffic conditions. Two main categories of performance models have been developed: flow level models and packet-level models.

Flow-level models are idealized models that include random flow-level dynamics but use highly simplified models of the bandwidth sharing operated by TCP. Based on the observation that TCP shares bandwidth in an approximately fair way, several authors proposed the use of the so-called processor-sharing queue as a performance model of access networks. This research direction was pursued to prove the insensitivity of the results to detailed traffic characteristics, to address stability issues and to account more precisely for the way TCP operates.

Packet-level models capture more details of the system (Round Trip Times, buffer size, etc.), but assume a constant number of persistent flows. Here, an important result has been the ``square-root formula'' for TCP throughput, which has allowed the development of several fixed-point algorithms to compute both flow throughputs and link loss probabilities. An important research effort has also been devoted to the analysis of TCP-like congestion control based on the optimization of some aggregated utility function.

Our research will attempt to fill the gap between flow-level and packet-level models, to integrate streaming traffics in the modelling framework and to extend flow-level models to general network topologies. We will also study queueing models taking into account the different peak rate limits of end user terminals.

A related research direction will concern server farms. Server farms are ubiquitous in applications ranging from Web server farms to high-performance supercomputing systems to call centers. Given the prevalence of server farms, it is surprising that even at this late date so little is understood regarding their performance as compared with their single-server counterpart, particularly with respect to scheduling. Our research will focus on the performance evaluation and the analysis of scheduling strategies in server farms.

Distributed Systems and Grid Computing

A related research direction will concern server farms. Server farms are ubiquitous in applications ranging from Web server farms to high-performance supercomputing systems to call centers. Given the prevalence of server farms, it is surprising that even at this late date so little is understood regarding their performance as compared with their single-server counterpart, particularly with respect to scheduling. Our research will focus on the performance evaluation and the analysis of scheduling strategies in server farms.

Deployment and management of applications (services) running within data centers or grids are more and more sophisticated. They are exposed to high demands and should ensure a steady high quality level. We think that access to remote services will be generalised in the next future for professional or private use. A solution to the underlying complexity will be the autonomic management for both remote and local executions. This involve automatic configuration and control not only for the distributed application but also for the computer, its operating system and the network, all depending on the state and the behaviour of the global system.

Dynamic Systems Filtering.

The Monte-Carlo like filtering approach (so-called particle filtering in the research community) will be forevermore left in favor of the deterministic approaches. Some recent results on joint maximum Bayesian likelihood filtering and smoothing using Gaussian mixture will be developed. Moreover, Gaussian mixture algorithms and more precisely the growing explosion of the number of densities induced will be better treated taking into account observability considerations.

On the other hand, the recent orientation toward image processing will be developed with some new application projects like fusion GPS-vision for autonomous robots and fusion visible-IR images for airplane navigation on airports. The BINAUR project (pedestrian navigation) will be extended to the military context through a REI request. Based on the ARSys project results, a new DGA (REI) project has been designed for 2009 with the industrial DSI. Three other projects are being negotiated in this sector: integrated SONAR processing (DGA);

autonomous GPS reception with low signal to noise ratio (Thales Avionics); guidance system for heavy torpedoes (DCNS).

Operatorial formulation and resolution of complex dynamic problems

This topic is the natural extension of the so-called *diffusive representation* approach. Operatorial formulations reveal themselves quite adapted for analysis, transformation and resolution of some complex dynamic problems encountered in modeling, design, identification, numerical simulation, estimation and control.

The complexity under consideration here relates to situations in which the evolution of some components of the problem cannot expressed under standard forms (i.e. by means of time derivatives and nonlinear ordinary functions), but necessitates to take into account *dynamic operators*, that is causal functions defined on *functional spaces of trajectories*. Such operators generate some specific difficulties for mathematical analysis as well as numerical treatment. At least in some particular situations, the currently available numerical tools make quite possible to elaborate numerical resolutions of such problems and so, it appears nowadays desirable or even indispensable to tackle frontally their study, by means of appropriate tools, in order to build efficient methodologies.

Some non trivial problems have already been solved following the operatorial approach. A the theoretical level, the open problems are yet numerous. The wide scope nature of this topic makes it compatible with a lot of practical applications in various fields.

Methods and Algorithms in Control – MAC –

Context and Challenges

MAC has had a long-standing tradition of producing original results in the field of robust synthesis and analysis for linear and nonlinear uncertain systems. From the original results related to quadratic stability in the early nineties, seminal works for LMI-based control, it has evolved towards the search for more complex Lyapunov functions, in order to analyze more complex system representations capturing more sophisticated behaviors. Moreover, numerical tools have been associated to build guaranteed certificates for analysis and control law design as well. In this framework, the group has capitalized a leader position at the national and international level as is illustrated by the list of publications. The objective for the future is first to perpetuate this recognition on fundamental aspects and to keep vivid our strong partnerships both with academic major research teams and industrial partners (CNES, EADS in particular). Further, the group is willing to enlarge its traditional basis with new research orientations that are described in the following.

The interaction between fundamental and experimental aspects is the cornerstone of the organization of the group to come. During past years, the group has focused on theoretic results when applications have most generally consisted in more or less complex artifacts relying on simulation software mainly provided by industrial partners. In that context, MAC invests time in developing, always at an upper theoretical level, research directions which intend to be useful for a large class of application domains and that are independent upon a particular instance. This does not prevent the group from being concerned with experimental devices. Indeed, a particular effort has been done in that direction during the last years, especially through internal and external collaborations. Such collaborations around practical preoccupations will be yet promoted in the future while the investment of the group in its own experimental platforms is rather evaluated as a threat than an opportunity.

Another threat, clearly identified, is the insufficient ratio between students and permanent staff that is below one. Attractiveness of motivated students of a high academic level to follow PH. D. studies at the interface between applied mathematics and engineering science is currently a crucial problem for the group. Consequently, a large majority of our Ph.D. students comes from abroad[1], thanks to well-established scientific collaborations. Sandwich Ph. D. students (co-tutelle or long term visitors) is also a tool that is promoted, both to enrich our collaborations and to increase the human potential of the group. More implication of the members of the group in teaching at undergraduate and graduate levels could also be used to attract students.

This context clearly shows that the basic research project of the group paves the way for fundamental advances in control theory, with a perpetuation and reinforcement of academic and industrial partnerships, in particular to access to complex experimental devices and to students. Indeed, modern control theory is used as a powerful tool to help at solving the following upper level challenging problems:

- Embedded optimization for autonomous systems, involving reconfiguration and recalibration of control laws particularly designed for energy management and safety improvement…;
- Help control law designers in reducing costs associated with ad hoc procedures of synthesis. This should consist in proposing guidelines for systematic synthesis methods and guaranteed certificates of robust stability and performances in order to reduce heavy test campaigns, typically using Monte-Carlo test strategies for analysis purpose of control systems;
- Feedback regulation and control of networks (electrical, information, biological…), in order to explicitly cope with time-delays and uncertainties, by using a priori dynamical modeling of usually observed phenomena;
- The development of new smart materials is a clear incentive to tackle different issues related to the distribution and decentralization of actuators: Distributed control for vibrations attenuation in flexible structures may be viewed as a typical instance of the general problem.

Their declination as fundamental issues is detailed in the following, associated with different applications and projects.

Major research orientations and projects

Introduction

The major research orientations of the group in the future will be supported by the classical triptych "modeling, analysis and synthesis". Therefore, all

[1] Half of MAC PhD students have foreign master diploma from Brazil (3), Mexico and Algeria. Eight out of ten are foreign students who have done undergraduate studies in their own country.

fundamental issues that will be privileged in the next few years are described in this setup.

Fundamental issues

"Modeling" — Besides the usual linear time-invariant (LTI) framework of our research activities, future orientations mainly concern new classes of models under consideration. The point here is to produce and use alternative models that should be able to adequately represent more complex phenomena (periodicity, distribution of parameters, flexible structures[3]) and include more detailed information as well (bilinear models, systems with isolated and/or piecewise non-smooth nonlinearities). The nature of considered models will be enlarged to include hybrid systems[2] (reset models for instance). Classically, these families of models will be completed by some appropriate uncertainty modeling. Indeed, those models are generally issued from practical problems provided from industrial applications for which robustness with respect to what is not exactly known or has been neglected is a fundamental issue.

"Analysis" — A central questioning for the group concerns properties analysis of linear or nonlinear dynamical systems. Both dynamical behavior (stability, performance in general…) and structural properties (inverse problems) are of interest. The historical context is based on Lyapunov theory, state space models involving uncertainties and disturbances rejection defined in the standard model setup. Recently, the group has begun to deal with polynomial representations involved at different levels of the model (ranging from state model to uncertainty). The major interest of manipulating polynomials is their strong relationships with occupation measures. This tool may be roughly considered as dual with respect to Lyapunov certificates allowing to get rid of additional variables in analysis tests.
In that sense, two complementary directions will be studied:
* Primal Lyapunov problem: It concerns the construction of positive definite Lyapunov (energy-based) functions, decreasing along the system trajectories, which are used as guaranteed certificates for stability and performances. Conservative analysis conditions may be expressed as semi-definite programming problems using convex relaxations based on sum of squares representations of positive polynomials for instance. The introduction of slack-variables issued from a particular application of Lagrangian duality to the original problem is another way to get a different set of conservative analysis conditions. The main objective of future research is to develop analysis conditions realizing a sufficiently good trade-off between exactness and conservatism so that they could be an alternative to existing Monte-Carlo tests widely used in the industrial context.
* Dual Lyapunov problem: The central idea is to eliminate the Lyapunov variables by directly working on the trajectories, thanks to the occupation measures (manipulated through their moments), in order to evaluate the stability and performance properties[3]. Conditions are also stated as LMI constraints jointly using real algebraic geometry (polynomials as modeling objects for control systems) and convex optimization (most notably semi-definite programming). This should pave the way for the development of new computer-aided control system design algorithms, including for example fixed-order robust and/or nonlinear controller design.

Future contributions of the group should be in new algorithms instantiating new competitive convex relaxations for multi-purpose robust analyses.

"Synthesis" — Analysis and synthesis steps are viewed as complementary stages sharing the necessity for computing a Lyapunov function certifying the properties of the closed-loop system in both cases. In the latter case, Lyapunov functions were traditionally used also to build the controller parameters. Some recent results to be generalized show that a powerful decoupling between the Lyapnunov function and the control laws allows to use more sophisticated certificates (parameter-dependent LF). More generally, the group is concerned with "box"-synthesis problems, where the box may be an observer, a control law or an anti-windup action... In every case, the synthesis problem may be viewed as an extension of the analysis one, with basically simpler models. Except for very special cases (stabilization via state-feedback for instance), open synthesis problems (multi-objective control, anti-windup design…) generally amount to solve NP-hard problems, and, particular heuristics for solution determination have to be investigated. As a matter of fact, the control system to be designed should satisfy heterogeneous functional specifications (stability and performance requirements, domains of safe behavior) with possible restrictions to the available information defining state or output feedback control problems. The original problem may be recast as a multi-objective optimization problem for which convex

[2] R. Goebel, R. Sanfelice, A. Teel, Hybrid dynamical systems. IEEE Control Systems Magazine, 29(2), 28-93, 2009

[3] J.-M. Coron, Control and nonlinearity. Mathematical Surveys and Monographs, 136, AMS, Providence, RI, 2007

relaxations are again the main tool to get satisfactory solutions in terms of the trade-off between numerical complexity and efficiency of the control system. It should be noted that the recent technological developments (formation flying, fly-by-wire aircraft, use of smart materials[4]) have induced new stringent requirements for the design of ad hoc control systems and the necessity to define more sophisticated control algorithms (decentralized or distributed controllers acting with partial information). Starting from the background of the group, the main evolutions in the future years will mainly affect the control law structure. From time-invariant state-feedback linear gains or full-order output feedback controllers to time-varying (periodic controllers) and nonlinear control systems (adaptive or, bilinear control laws), the idea is to extend the robust LTI framework to deal with the variability of the process (unmeasured model parameters) and variations of operation points in particular. Larger domains of guaranteed performance for these new classes of control laws are expected for systems for which LTI control systems action is structurally limited. Furthermore, the fact to take into account the heterogeneity of phenomena affecting a system (as mixed continuous/discrete descriptions, discontinuities in the state or the control, nested isolated static and dynamic nonlinearities...) is a very challenging task, not only from a point of view of modeling but also from an analysis or synthesis point of view. Aiming at improving performance and stability domains, adequate Lyapunov functionals and associated control laws could constitute a potential framework to account for such peculiarities in a systematic way.
In parallel, new topics emerge to enrich the research background of the group. In particular, the question of the design of robust optimal guidance strategies customary in aerospace applications (Rendezvous problem[5]) and in robotics (optimization of the pick and place strategy to reduce high speed vibrations) become an important future direction of research.
Optimal control theory is also used for the proof of some controllability properties.

On the other hand, some partial differential equation (PDE) models are now considered. As an upstream study of truncated models that are needed at least for numerical simulations, and in a very theoretical framework (including existence of solutions, well-posedness of problems, control issues…), the idea is to focus first on mathematical bases and modeling.

For instance, dealing with optimal or robust control, controllability or inverse problems for PDE in relation with applications is a great challenge. The inverse problem topic[6], which can also be described as parameter identification in infinite dimensional systems should also be considered from a practical point of view, for example in the case of biofilm growth for waste water treatment units[7]. Moreover, working on the analysis of numerical solvers for the optimal control of the Schrödinger PDE, the field of quantum control is approached. Finally, we plan to consider PDE models with time delays and to study them using the existing competences in time delay systems, field already well known in the group.

Applications and projects

A significant effort, already in progress but far from being completed, should also be done in the development of standardized numerical tools allowing some grey-box applications of the group theoretical contributions. New versions of the software GloptiPoly[8], RoMulOC[9], HIFOO[10] and a new toolbox dedicated to saturated and anti-windup control are planned for the very next years. Joint projects with industrial partners represent a strong motivation in this direction. Several important collaborations are described in the following.

Supported by the experience yielded from the GARTEUR projects on aeronautical applications, and the cooperative consortium AIRSYS (LAAS, IRIT, ONERA, AIRBUS), several members of the group have been involved in the NGCI ("Cockpit operational concept and key function") DPAC project since November 2009 (1 year renewable during 3 years). This project concerns various analysis and synthesis tools for improving longitudinal and lateral dynamics of civil aircrafts. This involves robustness aspects of feedback linearization, robust multi-model inversion for nonlinear systems, stability and performance analysis (robustness, resilient control, presence of nonlinear elements, switched control…), reconfiguration control (anti-windup strategies). Feedback linearization and anti-windup will be also the fundamental issues in an EDA project of the JIP-ICET program, entitled "NICE - Nonlinear Innovative Control designs and Evaluations", which

[4] HT Banks, RC Smith, Y Wang, Smart material structures: modeling, estimation, and control. Wiley-Masson, 1997
[5] J.T. Betts, Survey of numerical methods for trajectory optimization. J. Guidance, Control and Dynamics, 21(2), 193-207, 1998

[6] M.V. Klibanov, Carleman estimates and inverse problems in the last two decades. Surveys on Solutions Methods for Inverse Problems, Springer, Vienna, 119-146, 2000
[7] D. Dochain, P.A. Vanrolleghem, Dynamical modelling and estimation in wastewater treatment processes. IWA Publishing, 2001
[8] http://www.laas.fr/~henrion/software/gloptipoly3/
[9] http://www.laas.fr/OLOCEP/romuloc/
[10] http://www.cs.nyu.edu/overton/software/hifoo/

partners are, among others, Dassault, ONERA and Universita' di Roma "Tor Vergata".

CNES has proven to be a solid partner during the last period. This should not be contradicted in the future, considering the current projects and the new PhD grant (CNES-ASTRIUM) obtained for September 2009 to develop periodic controllers for the attitude control of agile flexible satellites actuated via magnetotorquers.

Other applications issued from various collaborations and associated fundamental problems should involve an increasing attention from the group in the next years. A non exhaustive list includes:

- Networks and protocols control like TCP/IP, involving time-delay control and observation. Indeed, modeling communication systems generally leads to dynamics models including delays, introduced by propagation and queuing phenomena. In this context, the design of AQMs (Active Queue Management), which are mechanisms located in routers in order to supply TCP for the congestion problems can be reformulated in term of feedback control problem. We faced then to the problem of the distributed output feedback which is solved using the robust framework adapted to the time-delay case[11, 12]. Another interesting feature is related to the problem of traffic monitoring (flow estimation and/or anomalies detection). This problem is reformulated into an observation problem with unknown input[13].
- Waste bio-treatment, integrative biology[14], in a general multi-scale and complex systems framework. All the modeling aspects are concerned, as much model structure and model properties, as model calibration[15]. Model reduction, observation and control issues are also to be addressed[16].

Further emerging applications are being discussed for few months and should also provide new questions and extensions of our classical background. In that context, anesthesia control is a challenging issue[17,18] which may be addressed by the group, in collaboration with scientists from the CHU Rangueil and industry (GE Healthcare). New generations of sensors and actuators (gas anesthesia instead of infusion anesthesia) and associated control strategies would be investigated.

Another facet of our projects is related to international collaborations. We intend, in the next years, to strengthen the links with our international partners thanks to the organization tools of the CNRS:

- A LIA with Brazil, whose French head will be Hisham Abou-Kandil (SATIE), is currently emerging. It exploits the mature links built between French (and in particular the group MAC) and Brazilian partners (in particular Pedro Peres (UNICAMP), Eugenio Castelan (UFSC), João Manoel Gomez da Silva Jr (UFRGS)…) in control and applications to mechanical devices and would facilitate exchanges of permanent staff members and students. Research topics are strongly related to the central research activities of the group, from robust control to nonlinear control and infinite dimensional systems (time-delay, smart actuators…) and a significant number of members of MAC will be involved in the LIA.
- A project is currently being written involving on the Japanese side academic researchers and engineers from JAXA. This project would give an official framework to a very promising cooperation that has been developed for the past four years independently of any specific financial support. Moreover, by involving JAXA as well as AIRBUS on the French side, it would enrich the cooperation by providing application examples on which to validate the theoretical results. The research topics will be robust performance analysis and robust time-varying control including LPV control, periodic control and simple adaptive control. A first step toward the reinforcement of

[11] R. Srikant. The Mathematics of Internet Congestion Control. Birkhauser, 2004.
[12] C. V. Hollot, V. Misra, D Towsley, W. Gong. Analysis and design of controllers for aqm routers supporting tcp flows. IEEE Trans. on Automatic Control, 47, 945–959, 2002.
[13] M. Fliess, C. Join, H. Mounier. An introduction to nonlinear fault diagnosis with an application to a congested internet router. In S. Tarbouriech et al. (Eds.): Advances in Communication Control Networks, LNCIS, 308, 327-343, Springer-Verlag, 2005
[14] Joint research program with LISBP, UMR-CNRS 5504
[15] K.V. Gernaey, M.C.M. van Loosdrecht, M. Henze, M. Lind, S.B. Jørgensen, Activated sludge wastewater treatment plant modelling and simulation: state of the art. Environmental Sciences and Artificial Intelligence, 19(9), 763-783, 2004
[16] I. Queinnec, S. Tarbouriech, G. Garcia, S.I. Niculescu (Eds.). Biology and control theory: current challenges, LNCIS 357. Springer Verlag, 2007
[17] J.M. Bailey, W.M. Haddad, Drug dosing control in clinical pharmacology. IEEE Control Systems Magazine, 25, 35-51, 2005
[18] C. Beck, H.-H. Lin, M. Bloom. Modeling and control of anesthetic pharmacodynamics. In I. Queinnec et al. (Eds.): Bio. & Ctrl. Theory: Current Challenges, LNCIS 357, 263–289, Springer-Verlag, 2007

the cooperation is the visit to LAAS of Yasuaki Oishi from Nanzan University for one year sabbatical starting from March 2010. This international cooperation involving AIRBUS for aircraft control applications may also, further, pave the way for a multi-laboratories proposal on aeronautic applications of control theory.

- Collaboration with Russia is currently supported by a PICS project, which has followed two bilateral projects. Prospects should be now considered under the form of an LIA or maybe a GDRI. The wish of the partners is to focus on scientific exchanges involving promising young researchers and Ph.D. Students. The topic is robust and adaptive control, intensively studied both in France and in Russia. In France the involved laboratories are LAAS and LSS. In Russia the partners are IPME (St Petersburg) and IUP (Moscow) institutes of the Academy of Sciences and Nizhni-Novgorod University. Another complementary project would be to build a joint European and Russian school for Ph.D. students on the given topic. It would involve support from European Union in the 7th PCRD framework.
- New cooperative projects with Italy should soon begin. The group will be involved in the GDRE "contrôle des équations aux dérivées partielles" (CONEDP) whose head is Fatiha Alabau (Univ. Metz). This GDRE starts in January 2010 and will promote research between French and Italian laboratories on that subject. Our activities on control problems of hyperbolic systems and inverse problems are supported by this GDRE. A CNR-CNRS bilateral proposal should also been submitted to cooperate with the Politecnico di Torino (Roberto Tempo and Fabrizio Dabbene) on robust control theory. Other actions have also been started up with Univ. di Roma “Tor Vergata” (Luca Zaccarian) and Univ. di Napoli “Parthenope” (Marco Ariola) relative to nonlinear elements in the control loops and to stabilization of time-varying systems.
- The group has a long-standing collaboration with the Czech Republic, and more specifically the Faculty of Electrical Engineering of the Czech Technical University in Prague (ČVUT), and the Institute of Automation and Information Theory of the Czech Academy of Sciences (AVČR). Since 1996, this collaboration has been formally supported by several bilateral Barrande projects, several bilateral CNRS-AVČR projects, a NATO project, and an ECONET project involving other central and eastern-european countries. Research activities focus on the use of polynomials and polynomial matrices in systems control, following the pioneering work of Vladimír Kučera in Czechoslovakia in the mid 1970s. In future we are planning to reinforce these links, in particular via common PhD fellowships (cotutelle). We are planning to extend the collaboration to the Mathematics and Physics Department of Charles University, and to other Faculties of the Czech Technical University in Prague.

In addition, several other collaborations will be carrying on with other usual partners such as USA, Chili, UK, Spain, Belgium… An objective will be also to obtain an official visibility for some of those collaborations which are sometimes only supported by own resources of the group.

Modelling, Optimisation and Integrated Management of Systems of Activities – MOGISA –

Context and Challenges

Context

The MOGISA group works on disciplinary topics from operations research, artificial intelligence, and control of discrete-event systems. The theoretical problems addressed are on production logistics, task scheduling, resource allocation, vehicle routing problems (VRPs), and more generally on combinatorial optimisation and constraint satisfaction. Specific applications are on frequency allocation, on-demand transportation, route planning in multimodal transportation networks, waste collecting, and railway maintenance.

Concerning its personnel, the MOGISA group knew deep mutations in the last three years. In 2008 and 2009, two professors, Gérard Fontan and Jacques Erschler, retired. Moreover, Colette Mercé (the currently last professor of the MOGISA group) took the direction of the Industrial Engineering and Computer Science Department of the INSA engineer school in 2008. Note that this last element may imply that the research activity concerning the supply chain management decreases in this prospective.

All that induces an important outflow of senior researchers in the group (only 2 CNRS researchers with "Habilitation à Diriger des Recherches").

On the other hand, 3 young scientists joined the group since 2006: Christian Artigues (CNRS, 2006), Laurent Houssin (UPS, 2007), Nicolas Jozefowiez (INSA, 2008).

Moreover the group enjoys good attractivity for PhD students: 5 new coming in October 2009 (3 in 2005, 2 in 2006, 4 in 2007).

In addition, the group aims at consolidating its leadership in Toulouse concerning OR (MOGISA has a major contribution in the organisation of next ROADEF Conference; see www.roadef2010.fr), and at federating and promoting research projects in this domain.

However, the MOGISA group needs to strengthen its international visibility in order to attract excellent candidates worldwide for postdoctoral positions and invited senior researchers.

An opportunity for the group is its recent participation to the ANR "Blanc" project ROBOCOOP on robust and cooperative scheduling (see Section 2.D).

Challenges

Nowadays, important societal concerns are the energy savings, the consideration of environmental constraints, which induces the use of clean and safe power sources, as well as quality of service expectations.

Associated with the research topics of MOGISA group, the main challenges we propose to take up mainly lean on the optimisation of production logistics and on the optimisation of transportation systems.

In real-life context, these issues find examples in: the production management in manufacturing industries, the reduction of traffic jams, a better use of existent infrastructures, rationalisation and facilitation of public transportation, etc.

Doing a correspondence with OR topics, this justify to reinforce or develop new research on planning and scheduling techniques with energy consideration, multiobjective optimisation, dynamic behaviours and uncertainties, and multimodality.

Therefore, we will extend our fundamental research work on alternative tree search methods for combinatorial optimisation including trends in multiobjective and robust issues, while keeping scheduling (in manufacturing, services, and computer systems) and vehicle routing as our preferred target problems.

Major research orientations and projects

Discrete optimisation / Constraint satisfaction

"New trends in mathematical programming for multiobjective integer programs" — A research will focus on problems that can be modelled as integer programs (and more specially 0-1 integer programs) and having several objectives. To solve these problems, we will work on the design of new efficient methods based on mathematical programming. They can be separated into two classes: a) Exact methods for multiobjective optimisation: These methods (branch-and-cut algorithm for instance) are important as they will permit to validate faster but approximate methods by providing the optimal Pareto set (see Fig. 1). Presently, the few exact methods that exist for multiobjective optimisation are limited and none uses integer (or even linear) programming; b) Advanced heuristics for multiobjective optimisation: Approximate methods must be considered to solve complex or large-size problems. However, it seems important to escape from adaptations of metaheuristics such as evolutionary algorithms that are the main methods used nowadays. The work will focus on what methods described as Math Heuristics, *i.e.*, methods that are not exact but rely on the power of exact solvers to provide good results on some parts

of the problem. For instance, it is necessary to see the possible contribution of methods based on integer programming (IP) like local branching [Fischetti and Lodi, 2003] and preprocessing techniques that have been proved effective in classical optimisation.

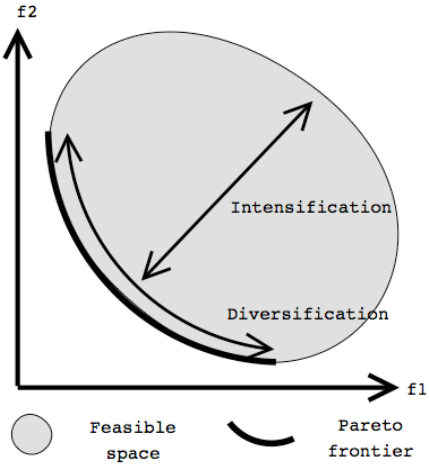

Figure 1: Multiobjective optimisation

"Discrete robust optimisation (DRO)" — Following the results we obtained on discrete optimisation methods in a dynamic context and on robust scheduling, we aim at proposing new models and methodological advances for discrete robust optimisation with a special focus on scheduling, network design, and telecommunication applications. On the basis of reference work in discrete robust optimisation [Kouvelis and Yu, 1997], several directions have been explored for robust counterpart of optimisation problems, which is often considered as too conservative [Ben Tal and Nemirovski, 1998], [Bertsimas and Sim, 2004]. However new approaches better adapted to the considered applications have to be found. For the method level, even when uncertainty is represented by intervals on data, recent results for maximal regret minimization, which involves particularly hard mixed bi-level programs, show a lot of room for improvement [Assavapokee *et al.*, 2008]. Improving the state-of-the-art algorithms and proposing new ones, in particular adapted to scheduling problems, is a research direction we will pursue, possibly but not exhaustively through decomposition mathematical programming methods and constraint programming (CP).
For the scheduling DRO models and methods, we will collaborate with all the partners of the ROBOCOOP project (see Section 2.D) and with Roel Leus of the Faculty of Business Administration of the KU Leuven (Belgium). For the network design side, we applied for a grant in the context of the French-Belgian "Tournesol" program with Olivier Brun from the LAAS-MRS group and Bernard Fortz from the Computer Science Department of Université Libre de Bruxelles (Belgium). For the telecommunication aspects, a PhD student co-funded by the GISTDA (Thai Ministry of Science and Technology's Space Agency) and the French embassy in the context of the THEOS project started in September 2009 his research on frequency allocation in satellite communication systems using (robust) discrete optimisation methods.

"Constraint Satisfaction Problems" — A short-term prospect is to experiment the discrepancy-based approach initially developed to process CSPs for the solving of optimisation problems. Scheduling problems with time lags (see Section 2.E) are privileged to do such experimentations.
In order to tackle heterogeneous problems (variables and constraints of various types), we propose to work on new propagation techniques for mixed and conditional CSPs [Gelle and Faltings, 2003]. This work will be done in collaboration with Fehmi Hmida from MSSDT, Tunisia. This can particularly serve configuration and design processes frequently encountered in the automotive industry for example.
Moreover we will continue to do research on generic propagation mechanisms but with some new considerations such as energy constraints (see Section 2.B).

Scheduling

"Cyclic scheduling" — The evolution of computer architectures, *e.g.*, VLIW architectures, gives rise to instruction scheduling problems that have to be solved at the compilation level. The latter features allow the use of static scheduling methods rather than real-time scheduling techniques traditionally used in computer systems. Unlike for standard cyclic scheduling problems mainly defined on single or parallel processors, complex cyclic resource-constrained scheduling problems are obtained, involving non-unary resources capacities and requirements (see Fig. 2).

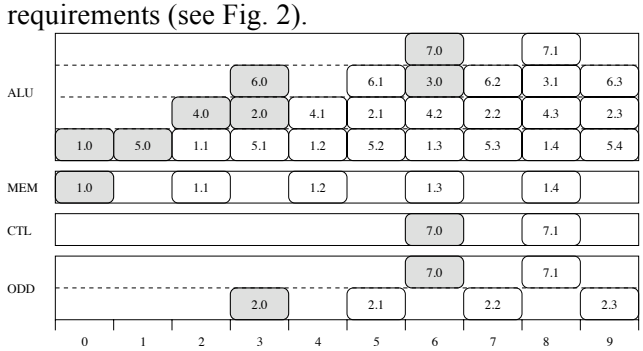

Figure 2: Resource-constrained cyclic scheduling

New models and methods are needed to tackle these problems, which are fundamental due to the use of VLIW processors in embedded systems. To support this research, we will carry on our collaboration with Claire Hanen and Alix Munier from the LIP6 and Benoit Dupont-de-Dinechin from ST-Microelectronics.
Also in this topic, an interesting track is to investigate the particular algebraic structure of (max,+) algebra

to provide efficient methods to evaluate schedules in cyclic job-shop scheduling. For example, the "heap of pieces" theory (see Fig. 3) associated with discrete optimisation methods enable to compute the best *K*-periodic schedule with a given *K*. This original approach constitutes for further research on scheduling theory.

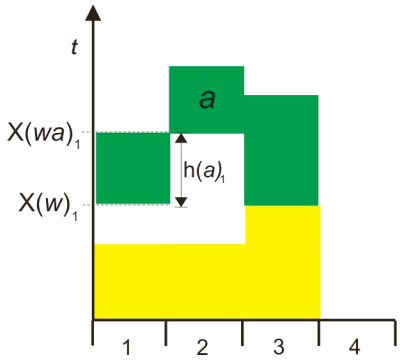

Figure 3: Heap of pieces theory for scheduling

"Energy-aware scheduling" — Power management and energy-aware scheduling are well-known critical issues in real-time and embedded computer systems and networks [Irani and Pruhs, 2005]. In production and/or project scheduling, the focus on energy consumption reduction is relatively new and constitutes today a major challenge for environmentally responsible industrial activities. Activity planning with energy considerations is also one of the major topics of the **ADREAM** LAAS project. We will propose new models and methods linked to energy considerations in scheduling through new types of constraints and/or objective functions. We will first focus on generic scheduling problems with energy constraints and/or objectives, then on industrial applications. The complexity of elementary problems will be studied. Dedicated heuristics, local search, metaheuristics, branch-and-bound, constraint-based scheduling, IP will be proposed. In particular, defining new global energy constraints in the CP paradigm, extending the standard energetic reasoning techniques issued from the group is a promising research direction. A multidisciplinary research project funded by the CNRS (GIMEP) in collaboration with the Chemical Engineering Lab of Toulouse will support a part of this research in 2009/2010 with applications in the process industry.

"Complex multiobjective scheduling problems" — One of our new research directions will be devoted to complex scheduling problems. By complex we mean scheduling problems involving non-standard constraints and/or objective, and in particular multiobjective scheduling problems. Tackling several objectives is one of the major issues for cutting edge research in scheduling [T'Kindt and Billaut, 2006]. In terms of computational complexity, several open problems are particularly challenging. In particular we will study the case of machine scheduling problems with setup cost minimization considered jointly with due-date related criteria. Discrepancy-based search procedures will be soon evaluated on flexible scheduling problems such as, parallel machine with precedence constraints and sequence-dependent setup times, 2-stage hybrid flow-shops, and flexible job-shops. On the constraints side, besides the integration of energy constraints presented above, we will also propose exact and heuristics methods for resource-constrained project scheduling involving one or several complicating constraints, such as generalized precedence-constraints, setup times and resource unavailabilities. To close the loop, multiobjective scheduling, in terms of exact solving methods, has mostly been applied to machine scheduling problem. Hence, an unexplored and exciting area is to propose efficient exact methods for more general resource-constrained scheduling problems involving several criteria.

"Cooperative and robust scheduling methods" — Besides the application of robust optimisation to scheduling, we will also study more specifically the interactions between robustness and cooperation in scheduling. Indeed, recent advances in information technology make the development of cooperative scheduling systems nowadays effective, particularly in applicative fields such as supply chain management, project management, timetabling, grid computing, etc. Nevertheless, existing systems often restrict cooperation to the basic exchange of structured information, just allowing the decisional actors to coordinate themselves. Beyond this first functionality, a natural evolution is to allow actors to collaborate, enabling them to negotiate their decision together in order to enhance the efficiency of the whole organization. While natural, this evolution is also much more complex. Many questions arise: How decisions should be negotiated? How robust scheduling techniques can help to enhance the efficiency of an organization? How to measure this efficiency? How cooperation mechanisms can be implemented? All these questions refer to the context of ROBOCOOP ANR "Blanc" project launched in 2009, with partners from LI Tours, LITIS Le Havre, and IBM-ILOG.

While in most existing OR approaches, scheduling is often seen as a global decision function where decisions concern the organization of the entire resource set, in a cooperative framework, resources are distributed among a set of actors having their own decisional autonomy, their own decision objectives and a restricted knowledge of their environment. Thus, this kind of distributed organization is precisely the context where robust decision methods can be profitable since each decision centre (DC) has to face, not only the unexpected events coming from

its own organization, but also and particularly those arising from its environment, including the other DCs (see Fig. 4).

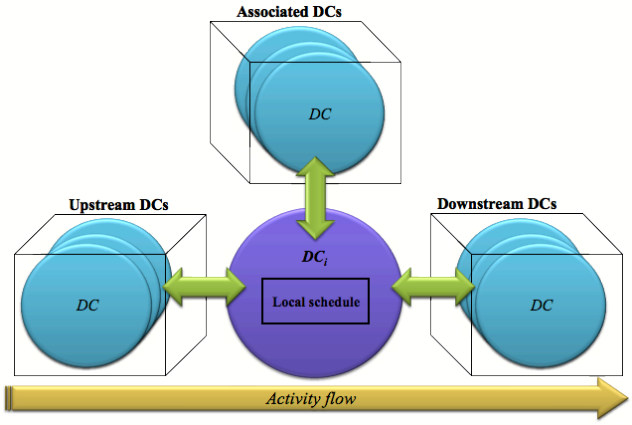

Figure 4: Robust and cooperative scheduling

In further works, considering the RCPSP environment and assuming that each DC manages its operations in a robust way, we aim at identifying the nature and the characteristics of the variables that are shared and negotiated between DCs in order to propose a mathematical formalism for supporting the cooperative behaviour of DCs. Indeed, since the negotiation processes have to lead to an efficient global organization (minimizing the whole project duration in the RCPSP case), while leaving each actor free to optimise its own objective, a trade-off has to be found. We think that studying this trade-off problem from a mathematical viewpoint (for instance considering decomposition techniques coming from IP theory, multiobjective optimisation, or CP) is a promising research track. The goal is to provide quantitative indicators that enable to measure the negotiation performance and to improve the quality of the DC decisions. Such an approach significantly differentiates this work from other AI cooperative agent-based techniques, which also addressed the negotiation problem, without providing neither performance indicator nor mathematical formalism.

"Scheduling with minimum and maximum time lags" — Considering the RCPSP/max problem, independently of makespan minimization, it is well-known that finding a resource-feasible schedule that respects both minimum and maximum time lags is NP-hard whereas, for the standard RCPSP, this problem is polynomially solvable. We also recently proved that the apparently simpler problem of inserting a single activity inside an existing schedule subject to min/max time lags, preserving the initial partial schedule structure, is NP-hard. Nevertheless, because we think that dealing with min/max time lags remains a challenging issue both from a theoretical and a practical viewpoint, we intend to pursue our efforts on this track. We particularly aim at studying the various ways of relaxing time-lag constraints in exact or approximate solving procedures.

Since new resource propagation mechanisms, based on the determination of longest paths in a constraint network, have been recently devised, we now plan to embed these techniques in a tree search procedure to solve job-shop problems with min/max time lags. The selected procedure is the method YIELDS, which successfully solved CSPs. Flow-shop problems with time lags can also be studied to evaluate and validate the approach.

"Event-based MIP for the RCPSP" — We also plan to work on new mixed integer programming (MIP) formulations for the resource-constrained project scheduling problems (RCPSP). Instead of relying on the traditional discretization of the time horizon, we propose formulations based on the concept of event. These formulations may present the advantage of involving fewer variables than the formulations indexed by time. Because the variables of this type of formulations are not function of the time horizon, we have a better capacity to deal with instances of very large scheduling horizon. Moreover, RCPSP problems involving a wide range of processing times are now common in industry but are not represented in classical benchmarks. We will then propose new instance sets involving such features. Finally, another feature of the event-based formulations is that they are theoretically able to process instances with non-integer processing times.

Logistics and transportation

"Production planning" — Traditionally, the planning of a production system is computed with MRP-based method. Most of them use linear programming (LP) approach. However, the deterministic characteristic of the LP approach yields a planning which does not always fit with the reality of the system. Few approaches, mainly based on Model Predictive Control have considered the problem with an automatic control viewpoint. Closed-loop methods (*e.g.*, Linear-Quadratic-Gaussian controller) applied to production systems seem to be a relevant area of research.

In this framework, the stability problem of the system appears. Usual techniques based on state matrix eigenvalues of the system can be used. Nevertheless, stability of the system is highly sensitive to the parameters of the system. For production systems, data such as transportation times, processing times or storage capacity, are difficult to estimate. Interval analysis provides efficient techniques to evaluate the stability of the system.

Finally, a supply chain can also be considered as a dynamic system in which inputs and outputs correspond to the product flows. These systems are usually subject to constraints due to the internal

structure of the chain (stock capacity) or the nature of products. We will investigate the use of (max,+) algebra as a tool to provide new innovative controllers for the supply chain management.

"Complex path computation and vehicle routing" Evolution of transports yields a huge need of path computation integrating complex constraints and objectives. In particular, the rapid expansion of multimodal passenger transportation makes the standard shortest path algorithms obsolete. Recently, new algorithms were proposed in this direction for time-dependent networks [Nannicini *et al.*, 2008], but new needs arise for user preference modelling in the multimodal context and efficient integration of these preferences in optimal path computation algorithms. We launched in 2008 a CIFRE PhD thesis in collaboration with the MobiGIS Company, and we have now a better specification of the requirements. We will intensify in the near future our effort for designing fast algorithms to fulfil these requirements in a multiobjective context.
We will also carry on our work on complex VRPs. In the context of a CIFRE PhD thesis started in 2008 in collaboration with SNCF and Michel Gendreau (CIRRELT, Montreal, Canada) we will propose methods to solve the Rail Track Inspection Scheduling Problem, an arc-routing problem with capacity, time windows, and a heterogeneous fleet. To tackle these problems, hybrid metaheuristic methods embedding column generation will be investigated.
We will also study some dynamic aspects of VRPs. This will be realized for the optimisation of on-demand transport systems near Toulouse (Tisséo).

"Multiobjective problems for transportation systems" — The main goal of the project is to reproduce the breakthrough of classic optimisation in the field of land transportation for multiobjective optimisation. The objectives we aim for achieving are threefold: a) The first one is to identify key objectives arising in land transportation and based on them to define problems that can serve as basis for more advance work in the same way that the travelling salesman problem or the capacitated VRP serves as basis for more advance problems in the case of classic optimisation; b) The introduction of these problems will not be sufficient if there is no way to solve them efficiently or to prove their efficiency. Multiobjective methods have known a steady growth for the last twenty years, but it can be said that the research tends to grow stale as the great majority of methods relies on evolutionary algorithms and it can be argued that the existing methods are crude adaptation on classic methods. Therefore, there is a need to develop efficient multiobjective methods, new advance heuristic built with a multiobjective optimisation point of view from scratch, and also a need for robust and fast algorithm able to generate a Pareto front (or at least a good approximation) in real-time. This part is linked to the first point of this prospective; c) The last objective is to provide a decision support system integrated with geographical information systems and the problems and methods found during the project to provide tools that can be used in the academic world as well as an industrial basis for real-life application.

"Interdisciplinary approach for the vehicle routing problem" — Human factors and dynamics aspects are generally ignored in the classical approaches to solve the VRP. We then propose to work on an interdisciplinary method for the logistics of transportation. This study could focus on the design of a generic architecture for the VRP, doing a link between methods of operations research (specific methods to solve VRPs and CP techniques) and a work domain analysis technique (based for example on an abstraction hierarchy, and identifying the real constraints involved during problem solving) coming from cognitive ergonomics [Vicente, 1999]. This study done in collaboration with Julien Cegarra (CLLE Lab – Cognition, Language, Ergonomics) will be the starting point for the ecological interface design suited to the problem. For its validation, contacts with a company involved in waste collecting have been established. We are going to propose an interface able to take into account all the problem variables just as three different problem cases: home rubbish collection, industrial waste collection, and recyclable product collection.

References

[Assavapokee *et al.*, 2008] T. Assavapokee, M.J. Realff, J.C. Ammons. Min-Max Regret Robust Optimisation Approach on Interval Data Uncertainty. *Journal of Optimisation Theory and Applications*, 137(2):297-316, 2008.

[Ben Tal and Nemirovski, 1998] A. Ben Tal, A. Nemirovski. Robust Convex Optimisation. *Mathematics of Operations Research*, 23(4), 1998.

[Bertsimas and Sim, 2004] D. Bertsimas, M. Sim. The price of robustness. *Operations Research*, 52(1):35-53, 2004.

[Fischetti and Lodi, 2003] M. Fischetti, A. Lodi. Local branching. *Mathematical Programming*, 98(1-3):23-47, 2003.

[Gelle and Faltings, 2003] E. Gelle, B. Faltings. Solving Mixed and Conditional Constraint Satisfaction Problems. *Constraints*, 8(2):107-141, 2003).

[Irani and Pruhs, 2005] S. Irani, K. Pruhs. Algorithmic problems in power management. *SIGACT News*, 36(2):63-76, 2005.

[Kouvelis and Yu, 1997] P. Kouvelis, G. Yu. *Robust discrete optimisation and its applications*. Kluwer Academic Publishers, 1997.

[Nannicini *et al.*, 2008] G. Nannicini, P. Baptiste, G. Barbier, D. Krob, L. Liberti. Fast paths in large-scale dynamics road networks. *Computational Optimisation and Applications*, 2008.

[T'kindt and Billaut, 2006] *Multicriteria Scheduling: Theory, Models And Algorithms*. V. T'kindt, J.-C. Billaut (Eds), Springer, 2006.

[Vicente, 1999] K.J. Vicente. *Cognitive work analysis: toward safe, productive, and healthy computer-based work*. Mahwah, N.J., Lawrence Erlbaum Associates, 1999.

NOnlinear DYnamics and Chaos – DYNOC –

Permanent Staff:
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Context and Challenges

The group DYNOC ("DYnamique NOn linéaire et Chaos", Nonlinear Dynamics and Chaos) will be a new one in the MOCOSY Research Domain of LAAS. This group is presently a part of the SYD group from LATTIS laboratory, which is going to join the LAAS in January 2011. It includes 6 permanent researchers.

When modelling physical systems, scientists and engineers often don't take into account nonlinearities, or consider them as negligible. Nevertheless, we know since more than half a century that nonlinearities generate specific phenomena, which have to be considered in order to understand fully the behaviour of the system under study.

Complex and chaotic dynamics, as it will be considered in the future DYNOC group, is a branch of the nonlinear system theory. Its foundations lie in the works of the Andronov's school, a Russian researcher of the 1930s; these works have been continued by American scientists from the 1950s (Smale). After that, many researchers throughout the world have worked and developed researches on Nonlinear Dynamics in various disciplines like pure or applied mathematics (Sharkovskii in Ukraine, Yorke in the USA), physics, engineering (Hayashi in Japan), chemistry, biology, economics,… In France, Mira has worked in this field from 1970s [1]; he created the SYD group.

In our group, continuous-time and discrete-time nonlinear systems are considered; models are analyzed using analytical and numerical methods.

Most of our studies concern the analysis of non linear systems modelled by maps, including bifurcation study and complex behaviour understanding, focusing more particularly on chaotic behaviours. Such phenomena can be unwanted and it is then necessary to perfectly understand them in order to avoid them; in other cases, complex and chaotic behaviours are required for specific applications and it is necessary to know them in order to provoke them; finally, if they cannot be avoided and are intrinsic to the system, it is necessary to understand and to model them.

All our research involves both theoretical and applicative aspects, from different areas. The following applications are considered:

a) Study of nonlinear circuits in order to understand the "routes to chaos" in the parameter space,

b) Modelling of evolutionary systems with applications to biology, ecology or economics,

c) Applications of chaotic signals to transmission systems; it is then necessary to study specific characteristics of such signals in order to consider new waveforms, which can be used for specific applications.

For our studies, we take advantage of the various origins of the members of the group: they come from applied mathematics, computer science and cryptography, signal processing and automatic control. We have created a synergy among all of them which can be seen as strength of our group and permits to view a large amount of potential applications. Theoretical studies and applications will be developed in the next section.

The group has developed several international collaborations in various areas; the corresponding projects will also be listed in the next section.

Considering nonlinearities and understanding complex behaviours in systems is a relatively recent way of thinking. Applications have appeared less than 20 years ago and have not yet reached the industrial world. This is a reason why it is not so easy to convince industrial partners of the interest of such studies. This point has to be strengthened by our group.

Another question concerns the difficulty to attract PhD students on theoretical topics, particularly French students. Most of them are more interested in research giving rise to applications.

Major research orientations and projects

Introduction

In this section, we detail the theoretical and applied studies which we intend to develop in the next years, as well as our current collaborations and some that could be developed with other groups of the LAAS laboratory (this will be investigated more thoroughly during the year 2010).

Theoretical studies

"Fundamental issues" — Our models are mostly described using n-dimensional maps, which can be obtained from the modelling of discrete processes or from the discretisation of continuous-time systems.

Complex behaviours appear already in low-dimensional systems and are not fully understood, even in the 2 or 3-dimensional cases. The consideration of low dimensional cases permits to focus on generic properties in order to better understand the way of leading to complex behaviours. The privileged approaches are related to qualitative studies of nonlinear dynamical systems, regarding the identification of the state space and of the parametric space. Specific fractal bifurcation structures have to be explained for such systems. Two are of particular interest, the “embedded boxes” (which include the period doubling cascade) and the “boxes in files” (also called “Arnold tongues”). These structures are well understood in the 1-dimensional case as they permit to understand two different “routes to chaos” [2] [5]; but in the n-dimensional case, n>1, even if these structures also appear, all possible mechanisms giving rise to chaotic behaviour are not completely understood and have to be studied in depth. In the next years, we will concentrate more particularly on the 3-dimensional case.

"Chaos generators" — One of the most important characterizations of chaotic phenomena is the sensitivity to initial conditions. Regarding applications, it is of interest to obtain a robust chaos that can be controlled in order to synchronize it.

Chaos issued from models of nonlinear circuits can be interpreted as signal that looks like noise; indeed it is non periodic and can show a wide frequency band. This property permits to use it as a random sequence or for applications in transmissions [7].

From a practical point of view, different kinds of oscillators can be considered but we need to determine if a purely analog circuit, a purely digital circuit or a mixing of both is preferable. There are many implementations of chaos generators in the literature. Some of them operate in continuous time such as systems based on Chua's circuit (analog), while others are discrete time systems which iterate a chaotic map (digital circuits). Continuous time systems with continuous value signals can theoretically produce perfect chaotic signals.

The problem with analog systems is that parameters and initial conditions are very difficult to set with a great accuracy, especially in a noisy environment. Iterative chaotic maps can be used to generate chaotic signals (chaotic sequences); parameters and initial conditions can be exactly known, but these systems can only produce signals taking discrete values and lead ultimately to periodic sequences.

Some other systems are based on so-called switching circuits where a latch (discrete value signal) is used to modify the behaviour of an analog circuit (continuous value signal) [3][4]. Systems mixing discretely valued dynamics with continuously valued dynamics are called hybrid systems. Discrete dynamics will offer versatility and spectral agility, and the continuous valued part will suppress the short cycles inherent to digital generators.

So, the understanding of “routes to chaos” in hybrid systems is of great interest (for instance the study of bifurcations in the parametric space, as well as the evolution of chaotic attractors).

A class of hybrid systems that we consider includes models defined by piecewise nonlinear maps (continuous or smooth). Their study will be conducted in collaboration with the University of Urbino, Italy.

We also consider hybrid systems including a continuous-time part. New tools and new algorithms have to be introduced for these studies. This is one of the aims of our collaboration with the University of Tokushima, Japan. This could also give rise to collaboration with the MAC group of the LAAS.

"New models" — In order to obtain a more complex behaviour and a robust chaos, one can expect that the consideration of systems of higher dimension can be interesting; time-delay systems can be a worthwhile alternative; theoretical studies of particular cases of such systems will be considered in a first step, in collaboration with the Universities of Piacenza and Urbino, Italy.

Another theoretical study, initiated at SYD-LATTIS three years ago, concern discrete maps with double indexes; the investigation of such models could help to understand some models described by partial derivative equations and is related to stochastic problems. The notions of periodic orbit, stability, bifurcation are completely different from those in the case of maps and have to be defined.

Applications

"Dynamics of population, biology" — Maps are used to model the evolution of several populations in interaction with each other. In collaboration with the University of Zaragoza, Spain, we have previously studied 2-dimensional models of different kinds of interaction: prey-predator, competition and symbiosis [6]; we intend to continue these studies in the 3-dimensional case, which means different kinds of interactions among three species. Some other applications in collaboration with researchers from Zaragoza concern the use of maps to model bi-stability or multi-stability in the brain.

"Transmissions using chaos" — The idea of using chaos to transmit information was proposed by the US Army Research Office through the report

"Toward a new digital communication technology based on nonlinear dynamics and chaos" published in November 1996. From this date, the number of studies has increased in this field.

Our work in this field concerns the use of generators of chaotic signals for transmissions. To cope with requirements of future communication systems, nonlinear carrier signal generators can be used. Many next generation communication devices will have to be able to change their transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. This alteration of parameters will be based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behaviour and network state. Nonlinear systems theory may allow proposing chaotic carrier signal generators with high spectrum agility. Using parametric chaotic signal generators will allow choosing adequately the frequency position and the bandwidth of the carrier signal (as a kind of link adaptation).

Theoretical studies have to be performed in order to establish connections between bifurcation phenomena and spectrum features of the output chaotic signals. Parameter estimation techniques, attractor's identification techniques, control of chaos techniques will be involved in this challenging task.

The key issue is then to propose new waveform generators that provide some kind of power spectral density agility. These generators must be easily implementable and reconfigurable non linear dynamic systems with low power consumption.

A Balaton PHC project (2009-2010 or 2011) is currently running with the Technical University of Budapest, Hungary, on new wireless communication technologies for sensor networks and embedded system applications both at protocol and at hardware levels. The aim is to use a modulation/demodulation principle based on chaos in order to propose systems with low complexity and low power consumption.

An ANR project "young researcher" is also going to be proposed on this topic, more centred on optimization and control of the signal spectrum.

Collaborations with the MRS group on parameter estimation and identification techniques could be set up.

Chaotic signals, being inherently ultra-wideband signals, are potential candidates for UWB communications [8]. The key issues in UWB radio are the implementation of UWB carrier generators, elaboration of new modulation schemes and detector configurations. Possible collaborations on UWB telecommunications systems could be discussed with the group MINC.

We also intend to continue our studies on telecommunication systems in collaboration with SC (Signal-Communication) group of the IRIT laboratory, which gave rise to very fruitful works in previous years.

"Chaos based security" — This topic, which has given rise to many studies, will be tackled under two ways:

- the use of chaos generators for frequency hopping,
- the possible cryptographical applications of hybrid chaotic systems.

The works on chaotic hybrid systems, with applications to cryptography, give us the opportunity to participate to the GDR DYCOEC ("Dynamique et Contrôle des Ensembles Complexes", Dynamics and Control of Complex Sets).

Internal collaborations

The topics of the new DYNOC group take perfectly place in the MOCOSY domain (analysis of nonlinear systems). Inside the LAAS laboratory, possible collaborations appear and will be discussed with different groups on modelling of nonlinear circuits, control theory, signal processing, identification, estimation and applications to telecommunications.

Organisation of conferences

The first issue of the international workshop NOMA (NOnlinear Maps and Applications) has been co-organised at Toulouse in December 2007 by the LATTIS-INSA and the University of Tokushima with the agreement of the IEEE France section. A second issue of this workshop has been organised at the University of Urbino in September 2009, also in collaboration with the University of Tokushima and the LATTIS-INSA. The third issue will take place in September 2011 in Portugal; the DYNOC group will be involved in the scientific committee of the workshop.

The group will organise at Toulouse in September 2010 the European Conference on Iteration Theory (ECIT'10).

Both conferences attract researchers from various disciplines, mathematics, economics, engineering,… and give rise to many fruitful and interesting discussions among these different fields.

References

[1] C. Mira, Chaotic Dynamics, World Scientific, Singapour, 1987

[2] D. Fournier-Prunaret, "The bifurcation structure of a family of degree one circle endomorphisms", International

Journal of Bifurcation and Chaos in Applied Sciences and Engineering, vol.1, n°4, (1991), p823-838.

[3] S. Banerjee, P.Ranjan, C.Grebogi, Bifurcations in 2-D piecewise smooth maps- theory and applications in switching circuits, IEEE Trans. Circuits Systems I, 47, 633-643, 2000

[4] T. Kousaka, Y. Yasuhara, T. Ueta, H. Kawakami, “Experimental Realization of Controlling Chaos in the Periodically Switched Nonlinear Circuit”, International Journal of Bifurcation and Chaos, Vol. 14, No. 10, pp. 3655-3660, 2004.

[5] D. Fournier-Prunaret, "Dynamical behavior in DPCM system with an order 2 predictor. Case of a constant input" Circuits, System and Signal Processing *Vol. 24, n°5, pp.* 615-638, Special issue "Applications of Chaos in Communications, *Birkhaüser Boston Inc.* (Jan. 2005), ISSN 0278-081X.

[6] R. Lopez-Ruiz, D. Fournier-Prunaret, "Logistic Models for Symbiosis, Predator-prey and Competition"" in Encyclopedia of Networked and virtual organizations. I ISBN SBN 978-1-59904-885-7. (Mars 2008)

[7] P. Chargé, D. Fournier-Prunaret, V. Guglielmi, "Features analysis of a parametric PWL chaotic map and its utilization for secure transmissions" *Chaos, Solitons and Fractals,Vol. 38, pp. 1411-1422, Elsevier Science, 2008.* (Jan. 2008), ISSN 0960-0779.

[8] G. Kolumban and T. Krebesz, “UWB radio: Digital communication with chaotic and impulse wavelets,” IEICE Trans. on Fundamentals of Electronics, Communications and Computer Sciences, vol. E90-A, no. 10, pp. 2248–2249, October 2007.

Research domain
Robotics and Artificial Intelligence – RIA –

Context and Challenges

The Robotics and Artificial Intelligence (RIA) area will put a renewed emphasis on one central subject of study: the autonomous robot. Indeed, there are still fundamental challenges linked to it.

The RIA groups will dedicate its research activities to perception, decision-making, motion, action, communication and interaction between the robot and its environment, the other robots and communicating devices as well as humans.

More research is necessary to explore the fundamental questions of the autonomous action in an open and dynamic environment. Challenges involve the investigation of more pertinent models and the development of algorithms, for interpretation and planning, which comply with complexity.

Models to explore will range from biomechanical to cognitive models, the models that are necessary to decide, to act and to interact. Besides, RIA researchers aim to investigate the essential and challenging links between numerical and symbolic models and the associated processes.

Other challenges concern learning, adaptation, situation assessment, principled methods for the construction and validation of integrated autonomous systems.

Major research orientations and projects

Based on this, RIA groups will be naturally involved in the two main strategic research stream defined at the laboratory level: the ADREAM (Architectures Dynamiques Reconfigurables pour Systèmes Embarqués Autonomes Mobiles) initiative and the interaction between life and systems.

RIA will contribute significantly to the LAAS ADREAM initiative. Indeed, this project gives the opportunity to study, at a realistic scale, the challenges of ambient intelligence. Indeed, several issues, raised in ADREAM, correspond to the RIA research groups projects such as the cognitive robot, sensor networks and the development of intelligent heterogeneous artifacts and their interconnection. ADREAM will provide a context to study, in a collaborative and multi-disciplinary approach, environments for the robot assistant.

The autonomous interactive robot plays a key role in such environments. Indeed, besides immaterial services that can be provided by fixed devices, the mobile robots allow the introduction of services that can be delivered physically or realized in a place that is determined on-line.

Another very important issue is the presence of humans, to which the services are dedicated and with which the robots have to interact. There is a strong need to take the humans explicitly into account at all levels: perception of humans and their activities, safe robot behavior, and also dialogue, assistance, cooperative human-robot task achievement, human-robot synergy, robot adaptation, compliance and pertinent reaction to the humans needs.

This aspect fits well with the strong involvement of the RIA groups towards the study of human. This is envisaged through a double perspective: (1) the study of the human in order to contribute with neuroscientists and psychologists to deepen our understanding of the human and (2) the elaboration and/or the refinement of models of the human that will help building pertinent robot behaviors towards the humans with whom it is assumed to interact.

Concerning interaction between life and systems, RIA will also devote strong efforts to the development of multi-disciplinary computational techniques and will contribute with MINAS to the investigation of multi-scale approaches combining the algorithmic efficiency of techniques issued from robotics with the accuracy of new physico-chemical models.

All these activities will be conducted in strong relation with the research teams at LAAS level and through intensive collaboration at national, European and international levels.

RIA will intensify its collaboration with researches from life and social sciences. Finally, the next period is also envisaged as propitious to enforced collaboration with industrial partners.

Gepetto

Context and Challenges

The prospective of the Gepetto group remains to *explore the computational foundations of human and humanoid motion*. After analyzing some strengths and opportunities of the research topic, this report presents the perspective for the coming period. It is based on the continuation of the current research (applied mathematics for improved algorithms and models, humanoid robot autonomy) and three research objectives reinforcing the synergy of Gepetto research with life sciences:

- biomechanics and robot motion planning for virtual mannequin simulation,
- neuro-robotics: towards a semiotics of the human motion.

Strengths

"A team with a solid theoretical background" — At the origin of the group, the background of its researchers comes from robot motion planning and control with good skills in algorithms (probabilistic approaches of motion planning) and control (nonholonomic and underactuated systems control).

During the passed period the purely robotics background of the group has been enlarged along two main directions:

- in terms of coverage, the group has gained competences in computational neurosciences (mainly thanks to the investment of P. Souères).
- from a theoretical view point, the group has gained new skills in numerical optimization and applied mathematics (mainly thanks to the stay of K. Mombaur).

A solid partnership: the research objective of Gepetto (to perform a research combining both human and humanoid systems) has been made possible thanks to a solid partnership on both:

- humanoid robotics supported by an effective exchange with researchers from AIST, and
- neurosciences with LPPA and CERCO.

Such a partnership will be active for several years via beginning common projects supported by FUI or JST-CNRS.

"An internal synergy within RIA pole" — the research conducted within Gepetto is coordinated with the two other robotics groups RIS and RAP at LAAS. With RIS we share common objectives in modeling human activities. While RIS is focused on human-robot interaction at a decisional level, Gepetto emphasizes on lower level motion control and modeling. With RAP, Gepetto shares a common culture in robot control and benefits from the skills of RAP in signal processing and robot perception. The three main objectives of the research program below constitute the contribution of Gepetto to the LAAS strategic axis opening its current researches to live sciences.

Opportunities

In terms of societal impact the research performed by Gepetto benefits from two main opportunities:

- the increasing impact of the Product Lifecycle Management in the industry. In that domain the simulation of virtual mannequins in the digital mockups remains a challenging issues. The long relationship between LAAS and Kineo company represents an asset.
- the recent period confirms the emergence of effective markets in servicing robotics at large including the humanoid robotics. The current project ROMEO as well as the recent partnership with Toyota represents opportunities to support the research project.

From a theoretical viewpoint the modeling of the human being is today a hot topic that requires coordinated pluridisciplinary actions gathering life sciences (neuroscience, biomechanics), human sciences and engineering.

Major research orientations and projects

Gepetto intends to maintain and develop its background while maintaining its objectives in terms of applications.

"Applied mathematics for improved algorithms and models" — from the point of view of the theoretical tools a special effort will be on the following critical topics:

- *facing the complexity of motion planning* for redundant and underactuated systems (e.g. anthropomorphic systems). In that perspective the recent results we have obtained on the automated control of random diffusion process by principal component analysis will be reinforced. We will also investigate new models of convergence.
- in the recent period we have introduced a new research paradigm to study the human motions. *Inverse optimal control* serves to identify the underlying optimality criteria of human motions from measurements. Based on these results optimal control models are established that can be used to control robot motion. Inverse optimal control problems are hard to solve since they

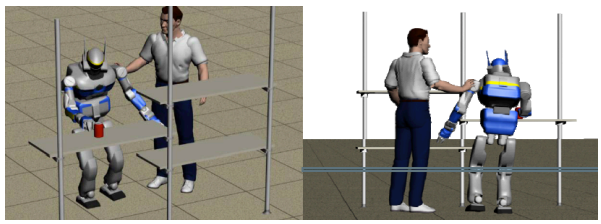
require the simultaneous treatment of a parameter identification problem and an optimal control problem.

"Robot motion autonomy" — Humanoid robotics will remain the main line of support to contribute to fundamental research in robotics at large. While an important effort has been done in the past period in term of motion planning and software integration, the next period will emphasize on *motion reactivity*. The approach will be based on a combination of tools coming both from geometric algorithm (planning side) and from control. The main scientific objective as described in the new project RBLINK is to allow very fast decision making to generate whole body motion. This will be achieved through building a bridge between the reactive and the deliberative approaches to overcome their respective weakness. Working on humanoid robot sums up almost all the problems of a generic and versatile robotic platform:

- the high number of degree of freedoms.
- the necessity to take into account the dynamic properties of the robot, and more specifically the stability,
- the necessity to take into account self-collision and joint limits.

Our approach is bottom-up in the sense that we are trying to solve problems which are challenging for a real humanoid robotic platform such as HRP-2 with respect to the current state of the art. We are also building our work on a practical remark: because from the robot designer side we have a complete knowledge of the robot it is possible to make massive pre-computation based on the model of the robot. On the other hand very few assumptions can be made on the environment. It is then possible to have asymmetric resolution of the problem where pre-computation can be arbitrarily long, but instant resolution has to fit the time constraints.

On the other hand, one of the main challenging issue in humanoid robotics is to prevent falling. The current approaches based on the so-called ZMP approaches are limited to locomotion on flat terrains. However a humanoid robot reacting to a dangerous situation might advantageously make contact with the environment to keep its balance and avoid the fall. New models (recently introduced by our partners INRIA, JRL and AIST) allow to consider multi-contacts. It remains that such models do not allow real-time decision making. Covering the constraints imposed by *motion reactivity* will constitute a critical facet of the research.



RBLINK: in case of disturbance the robot should be able to make use of all its body segments (e.g. legs, arms) to prevent falling.

Biomechanics and robot motion planning for virtual mannequin simulation

Motion planning technology is successfully used by software industry in the so-called Product Lifecycle Management domain. The simulation of virtual human beings remains today a bottleneck for broader applications in virtual reality. From our experience (e.g. within the ANR project PerfRV2) the efficiency of the available methods is based on geometric and kinematic modeling. Such models lie at the core of probabilistic motion planning algorithms that made the success of the research area. However the realism of the computed motion can not be validated from an ergonomic point of view. The models are too simplistic. We intend to go one step further by taking into account the whole body dynamics and the action of muscles.

Considering the whole musculo-skeleton model increases the dimension of the space search from 30 to more than 200. The first issue to be addressed is then to face the combinatorial complexity of the considered models. On the other hand, the objective is to model the motion dynamics. While the planning algorithms usually consider only geometric (for collision avoidance) and kinematic (for articulated systems) models, the challenge here is to account for the second derivative of the system variables (e.g. forces, energy consumption, gravity modeling).

Neuro-robotics: towards a semiotics of the human motion

Usually -at a first glance- robot autonomy is addressed along two main decisional architecture schools: the first one is based on a behaviorist approach suggesting that complex tasks emerge from elementary sensori-motor functions, while the second one is based on a centralized decision making cooperating with reactive controls. Both architectures are based on functional decomposition of the tasks.

In life science the biology of the decision making appears to be an active research topic. Animals and humans have evolved rapid and efficient decision-making processes to solve complex and conflicting choice situations. The opposition between deliberative actions and reflex actions, together with the respective locus of decision making in the brain

(frontal cortical areas *versus* basal ganglia) constitute current research challenges.

We propose to investigate this issue from the perspective of the computational motion viewed as a way to embody the action.

The question is first to explore the invariant parameters of a given action. In that direction we will pursue the inverse optimal control paradigm we have introduced for the study of the human locomotion.

The second question is to better understand what is the nature of the sensori-motor loops arising in the control of a task.

Finally we will integrate these models within the general framework of the redundant systems theory as follows.

In a recent work we introduced a novel method of guiding a humanoid robot, including stepping, by allowing a user to move "just" its head. The motivation behind this approach comes from research in the field of human neuroscience. In human locomotion it has been found that the head plays a very important role in guiding and planning motion. We use this idea to generate humanoid whole-body motion derived purely as a result of moving the head joint. The input to move the head joint is provided by a user via a 6D mouse. The algorithm proposed in this study is able to judge when further head movement leads to instability and then generates stepping motions to stabilize the robot.

This simple work accounts for the fact that a very simple task such as "look at" may can require complex motion as walking. "Walking" here is *motivated and activated* by "looking at" without any planning.

The objective of this research axis is to explore the foundations of a semiotics of the motion in order to improve the programming of complex robot systems. Such a semiotics will be based on a symbolic representation of the action from the numerical functions at the origin of the motions.

The approach requires to revisit the classical frontiers between numerical and symbolical models.

With the notion of stack of tasks introduced by N. Mansard in his PhD, a task appears as a submanifold (gathering the invariant parameters of the action), which is the kernel of linear projectors modeling the tasks to be done in parallel. The distinction between possible coordination or mandatory competition appears as the result of a numerical optimization algorithm.

How to make planning in such a framework? At which level does the symbol appear? There are the questions we want to address both:

- to provide high level programming language for robotics, and
- to propose new mathematical models whose pertinence in life science will be evaluated in collaboration with neuroscientists.

Such a research line will benefit from the convergence of complementary skills of Gepetto researchers in bio-inspired approaches to sensori-motor control, numerical optimization and simulation and redundant system theory.

Note: In the framework of the strategy aiming at stimulating the cooperation between LATTIS (INSA) and LAAS, discussions have been initiated between Gepetto group and the robotics team at LATTIS. Robotics at LATTIS has gained an original positioning well recognized at the international level. It focuses on the design of artificial muscles to control anthropomorphic mechanical structures. The bio-inspired approach of the team fits well with the research methodology conducted in Gepetto and, more globally within the RIA pole, with the topic of cognitive robotics (RIS) and robot control (RAP).

Robotics, Action and Perception – RAP –

Context and Challenges

During the 2011-2014 period, the RAP group, highly coordinated with the other groups of the RIA department, will keep on focusing its research on the functional capabilities of robotic systems executing tasks in dynamic and evolutive environments. As mentioned in several Robotics Roadmaps[1], several convergent evolutions classified hereafter as scientific, technological and applicative ones, will influence our future topics.

Many theoretical improvements in Signal Processing, Vision, Control Theory, Machine Learning, etc… have been recently proposed, but with relatively weak impacts on integrated robotics, i.e. few of these thematic contributions have been implemented on robots. One major role of the RAP group in the LAAS context, consists in studying advanced algorithms proposed in Control Theory, Vision…, deriving from them new methods for robotics applications integrating these methods on our robots, and proposing new contributions from the analysis and the evaluation of robotics experiments

Moreover technology is evolving very fast: new sensors (Time-of-Flight 3D optical sensor, micro-cameras, Indoor-GPS, RFIDs…), new computation units and architectures (GPU, FPGA…), new interaction channels between robots, environments and humans through wireless communications (Internet of Objects…), etc… are already available or will be developed in the next years. The RAP group intends also to update his know-how on the design and the implementation of robotics functionalities with respect to new technologies, and to evaluate how they could renew some robotic problematics.

Finally, the main robotic market for robotics applications has concerned industrial applications since the early beginning of robotics. The emergence of a market for service applications in human environments[2] has been announced for ten years, e.g. assistant robots for disabled or elder persons, companion robots at home, or service robots in public areas (commercial centers, transport stations…). Some companies are indeed developing robotics products, but only for specific tasks (vacuum cleaners, lawn mowers…), because robotic technologies are not mature enough to propose generic services. Indeed, actual robots are not robust, safe, reactive, reliable enough, they propose too poor human-robot interactions, their behaviour cannot be predicted or understood by humans…

As a participation to the transverse ADREAM program of LAAS, the main challenge during the next period, will be to study, develop and integrate on physical robots, all devices and functions required to execute generic tasks, but also to interact in a generic way, with the environment (benefiting from ambient intelligence) and with humans (understanding requested services, intentionality, activities…), and to learn from their observations.

RAP is able to contribute on this challenge, by taking advantage of the related scientific and technological improvements, and from fruitful cooperations not only with other RIA groups, but also with partners closer to applications in order to identify bottlenecks and socio-economical needs. RAP also benefits from the robotic platform of LAAS, with several existing demonstrators and new ones that are foreseen (especially the two-arms mobile platform).

RAP in itself, gathers specialists in Vision, Signal Processing, Estimation and Control Theory… which are many scientific domains required to develop robotics systems. Nevertheless, during the last period, the RAP manpower was not sufficient with respect to numbers of supervised PhD students and of on-going projects; for some research areas (Algorithm-Architecture Adequation), RAP in itself has not all the required technological background.

To overpass this weakness, RAP has developed many internal cooperations with other LAAS research groups: MRS for Estimation and Filtering, MAC for Control Theory or Optimization, N2IS for the design of integrated architectures, more recently OLC for the design of distributed systems… These cooperations have been developed through co-supervisions of PhD students or through the participation to joint projects (especially internal LAAS projects: by now, AudioHRP2). Outside LAAS, RAP has also active collaborations at the regional (IRIT, EMAC -Ecole des Mines Albi-Carmaux), national (LASMEA, ISIR…), european (Coimbra, Karlsruhe, Mondragon…) and international (Mexico, Colombia, Brazil, Japan…) levels. So RAP performs collaborative research projects both on theoretical topics and on robotics applications.

Recently RAP has received other collaboration propositions, and could develop new projects with CEA-LIST on visual monitoring, Aldebaran on embedded vision on humans, EADS-IW on airplane inspection, or ASTRIUM on vision algorithms integrated on dedicated hardware… RAP could be also an input gate for the integration of new sensors

[1] e.g.Robotics Roadmap made by a consortium of US Universities: http://www.cra.org/ccc/docs/0905662_CCC_Report_Screen.pdf

[2] Roadmap for service robotics : http://www.scribd.com/doc/15783483/Robotics-Roadmap-Service-Robotics

on robots, either on-the-shelf or designed and developed in the MINAS department (let us cite RFID antennas, or audio sensor).
Nevertheless RAP will have to be selective in the future in order to keep a good balance between fundamental and applicative topics, and to avoid saturations for the permanent staff.

Major research orientations and projects

During the next year, our research will still be based on PhD thesis or projects which have already started. Eleven RAP PhD students must end their works before January 2011. Many current projects (ANR R3T, AMORCES, RINAVEC ; FP6 CommRob…) must be over in 2010 or early in 2011.
In the next 2011-2014 period, some topics studied by now will be more deeply developed, e.g. visual navigation in cluttered and populated environments, object recognition and 3D modeling integrated in a manipulation system, Visual SLAM… More efforts will be devoted towards the visio-auditive perception of humans and the joint perception of humans with the environment: especially a completely innovative audio sensor will be designed and developed based on bio-inspired ideas (binaural sensor, active audition…).
But the more innovative work will come from the development of new functions in order to control the execution of robotic tasks in instrumented environments (Internet of Objects, Ambient Intelligence…) or to integrate technological innovations. How can a robot perform long-term navigation and manipulation tasks in a more robust, faster and simpler way… making profit of contextual information received from humans, from other robots, or from the environment, e.g. labels of objects or of specific places? How a robot can be more reactive when detecting new events, using new mixed architectures or new sensors?
The major research orientations for the RAP research group are detailed hereafter. For each topic, potential new collaborative projects are mentioned.

Robot navigation and ambient intelligence.

This topic is highly related with the ones described hereafter on *Cooperative strategies for the Monitoring of human environments,* on *Robot audition* and on *Active human-robot interaction from the joint human-environment perception.* Here environment monitoring (from sensors merged in the environment) is provided as a way to make more robust, faster and safer service robots belonging to several heterogeneous fleets. Some robots could interact with humans or "simply" navigate and share the space with humans i.e. interact passively.
Only some preliminary works using one robot detecting RFID tags disseminated in the environment, are currently on the way. The challenge will be here the dimensionality (large environment, many sensors, many robots, many humans…) and the heterogeneity (perception from data fusion between RFID, IR sensors, embedded and fixed cameras…). We aim to mount in the environment smart cameras, i.e. cameras with embedded processing and with wireless communication, so that the estimation about the current state (robots and humans positions and velocities, landmarks positions…) will be decentralized.
Many challenges will be addressed :

- the deployment of a sensor network : how to calibrate such sensors making profit of a robot moving in the environment ? How to integrate in the SLAM framework, RFID tags and cameras positions... ?
- a mixed architecture, combining local processing performed on each sensor nodes, decentralized fusion from local data exchanges and a centralized fusion on a central station, required for global interpretation.
- the friendly behaviour of robots in instrumented public areas, requiring many interactions so that robots and humans can perform joint tasks.
- data fusion from vision, RF and audio sensors (either embedded on robots or merged in the environment). For noisy public areas, bio-inspired strategies could be studied in order to develop new embedded active perceptual functions.

This topic will allow RAP to participate to the transverse ADREAM project, benefiting from the new instrumented LAAS building ; RAP will also participate to new collaborative projects that are currently prepared, i.e. the regional project CameraNet about visual monitoring by a network of smart cameras, a FP7 project about Cognitive Integrated Crosslevel architecture for networked robots an sensors systems in human environments , and a FUI project leaded by EADS IW about a service robot devoted to airplane inspection.

Cooperative strategies from embedded and deported exteroceptive sensors devoted to populated environments

The work on the visual perception of humans, will be extended, focusing on the fusion of heterogeneous and multi-modality data, from the cooperation of active or passive sensors, either embedded on robots or fixed in the environment.
The group will aim to develop integrated systems that can monitor simultaneously sensor streams, build a representation of what is currently going on in the scene thanks to probabilistic models. This system will be generically developed for and applied to the monitoring and control of crowded public environments. Our investigations will aim to add two

extra dimensions. First, all these processes will work through multi-sensory data fusion. Our strategy is here to sense multiple humans with deported sensors such as wireless networked and possibly active (PTZ) cameras, readers of RFID tags fixed on humans' clothes, infrared motion detectors, even networked microphones. Fusing such sensor streams is expected to improve the low-level human perceptual functionalities robustness to occlusions, data association problems in order to interpret scenario involving several humans. The second issue will concern the immersion and interaction of instrumented mobile robots/agents in such ambient intelligence. Mobile robots with their on-boarded perception/mobility abilities will allow to: (i) focus the perceptual resources on a given sub-space in order to complete the perception from the static sensors, and (ii) to interact with the other agents sharing the space e.g. to automatically follow a person in crowds.

These works will take place in the ADREAM context, leading to collaborations with other LAAS groups from the MINAS and SINC departments, and exploiting sensors and robots installed in the new instrumented building. New collaborative projects have been recently submitted on this topics, either with regional (CameraNet, accepted), Mexican (LEMONS submitted at International ANR CfP) or european partners. A new collaboration will start with CEA-LIST, through a PhD co-supervision.

Robot audition

The planned work on robot audition will follow several lines of research. First, hardware issues connected to the aforementioned integrated acoustic sensor prototype will be developed. The ongoing hardcoding of the localization and spatial filtering low-level functions on the FPGA will be finalized, and extensively checked against their working C/C++ counterparts. In addition, the manufacturing of a second set of hardware will be completed. The consequent new prototype will enclose the replication of the existing DAQ boards together with a new processing board including a last generation Virtex-5 Xilinx FPGA (instead of a Virtex-4 FPGA for the current prototype), all being designed at LAAS.

Besides, our theoretical approaches to localization and spatial filtering will be extended to a semi-circular array of microphones. Once the hardware is completed, these primitives will be hardcoded and the new integrated sensor will be mounted on the HRP2 humanoid robot hosted by LAAS. Concerning specifically the broadband beamspace MUSIC approach, an online detector of the number of sources will be designed along with the computation of the pseudospectrum for localization.

Within the framework of Julien Bonnal's doctoral thesis, the design and implementation of higher-level auditory functions will also be completed. These functions will take place in the C/C++ architecture of the above integrated auditory sensor prototypes. They will consist in voice activity detection, speaker recognition, and visual&auditory tracking. When they are operational, we will have at our disposal a fairly complete set of auditory primitives, which we will evaluate extensively in the uncontrolled and dynamic environments of Robotics.

Last, still concerning robot audition, we will start a new line of research in parallel to our work on array processing based methods. An original binaural auditory sensor will be built, based on the geometrical and computational foundations in humans, and mounted on the HRP2 humanoid robot. On this basis, low-level auditory functions will be developed for source localization, source separation, and voice detection. Importantly, whenever possible, these functions will be "active", in that they will integrate the robot motion and its proprioception.

These prospects constitute a subset of the recently accepted BINAAHR ANR project, LAAS will coordinated ISIR (Institut des Systèmes Intelligents et de Robotique, Paris), LPP (Laboratoire de Psychologie de la Perception, Paris), and Prof. Okuno's lab in Kyoto, which is the leading team in robot audition. The application aims are binaural active audition (first from a robotics viewpoint, then through a dialog between psychophysics and robotics) and advanced auditory H/R interaction.

Active human-robot Interaction from the joint Human-Environment Perception

The joint perception of humans and objects is challenging as any personal robot, while moving in our everyday environment, must learn by observation or by imitation. Providing robust definitions for every single object in such an environment is impossible in practice. The alternative is to categorize objects based on their affordance properties or how an object can be interfaced in order to capture the essence of an object's utility. Further investigations will focus on enriching the widely used structural object representation (what do objects look like) with functional representation (how can the person interact with them) as well as spatial/temporal associations with respect to the human's actions.

Previous works on human motion capture in 3D, multimodal command interpretation (from the theme *Perception on Humans*) and object modeling (from the theme *Perception on the environment*) will be here jointly considered; the formalism will be based on graphical models and Bayesian inference.

Our long-term research goal is to get personal robots able to observe and interact over long periods of time

in order to categorize objects or places by observing humans and to associate sets of actions or activities that can be performed with those objects or places. Beyond this learning step instructed by human tutors, the finality is to use information from scenes/objects to provide context when sensing un-experienced humans.

Perception in outdoor environments

This topic will be jointly studied with the RIS research group. While RIS will focus on multi-robots applications, especially on the coordinated perception of aerial and terrestrial robots, RAP focuses its work on perceptual functions embedded on terrestrial vehicles only.

Visual SLAM has been studied in order to compare different ways to initialize 3D points or straight lines perceived by one (Bearing-Only) or several (BiCam) cameras. This work will be continued, combining several features and integrating 3D reconstruction with an active feature tracking in image sequences. Moreover, the convoy configuration will be especially studied: how to learn a trajectory in the SLAM framework? How to execute a learnt trajectory, taking into account potential evolutions in the environment? Is the proposed approach robust enough to be applied on long trajectories (several kilometers) with or without loops?

Several projects are coping with Obstacle Detection from a vehicle navigating on 2D (FUI SART: airplane on taxiways) or 3D (ANR RINAVEC: robots in open space) terrains. The challenge here is how to segment an obstacle from the background on every image, how to estimate the obstacle states (positions, velocities, appearances) from an image sequence. By now we are evaluating an a contrario method in order to detect dynamic obstacles from a set of tracked points. This method will have to be integrated with region-based tracking and segmentation, so that obstacle limits could be clearly defined, and obstacles could be identified from their appearances, shapes, motions and deformations. Visual SLAM and Obstacle Detection will have to be integrated in the same framework (SLAMMOT) in order to estimate absolute object velocities.

Obstacles could be also detected from a navigability analysis of the terrain. For a 2D terrain, several attributes (color, texture, homographic rectification) are currently used to classify pixels as belonging to the ground or to obstacles. For a 3D terrain, 3D (given by a DEM) and appearance-based attributes will be integrated to build a navigability map.

Moreover, obstacle detection requires the maximal reactivity on the robot; so new algorithms must be studied both with dedicated sensors and architectures.

Coordinated visual servoing

Different research axes will be investigated in the future, in order to make more complete our current work on visual servoing. First of all, we plan to extend the work concerning the reconstruction of the visual features when they become unavailable during a vision-based navigation task. Indeed, the developed approach works when the necessary data are supposed to be perfectly known, but it appears to be less efficient when they are noisy. This is the reason why we are now developing a new approach to improve the estimation of both the visual features and their depth in such a context. The first results are promising but still need to be improved. Moreover, we also plan to enhance the multi-sensor-based control strategies which have been previously designed to deal with the problems of occlusions and collisions which may occur during a vision-based navigation task in cluttered environments. Indeed, up to now, the obtained results are restricted to static scenes. Therefore, our goal is to extend these works to dynamic ones where both reference landmark and obstacles may move. To this aim, we first propose to couple filtering methods with visual servoing techniques to make the robot follow a mobile landmark in a free environment. In a second step, we will address the problem of efficiently detecting the occlusion and collision risks when both obstacles and landmarks are moving. We will then design new control strategies allowing to make the vehicle safely evolve within such a complex environment. However, as robots and humans will have to share the same environment soon, it appears very important to extend the works initiated through the Commrob project. We then plan to develop robust control strategies allowing to make the robot safely move with respect to a given user while guaranteeing non collision not only with obstacles but also with other human beings. The problem of the reference user's occlusions will also need to be addressed. New challenging areas around "human-based visual servoing" will then be opened. Finally, to end this part dedicated to vision-based navigation, we would like to use visual servoing techniques to coordinate several (mobile or not) robots equipped with cameras. It would then be possible to benefit from the visual data provided by one (or several) robot(s) to help the other one to complete its mission. A network of active sensors could then be created and the range of realizable tasks significantly enlarged.

Finally, very recently, we have also started a new research activity centered on the vision-based control of a robotic system made of two manipulator arms. The idea is to use visual servoing to coordinate the two arms to realize typical "human" tasks such as open a bottle. To our knowledge, this problem has

not been addressed yet in the literature. We have already developed a control strategy allowing to recap a pen when one arm is kept fixed; we are currently extending this method to really coordinate both manipulators. First results have been obtained and clearly show the interest of using visual servoing to perform such tasks (see figure 1). An application of the sensor-based control strategies to humanoid robots will be also considered in the future.

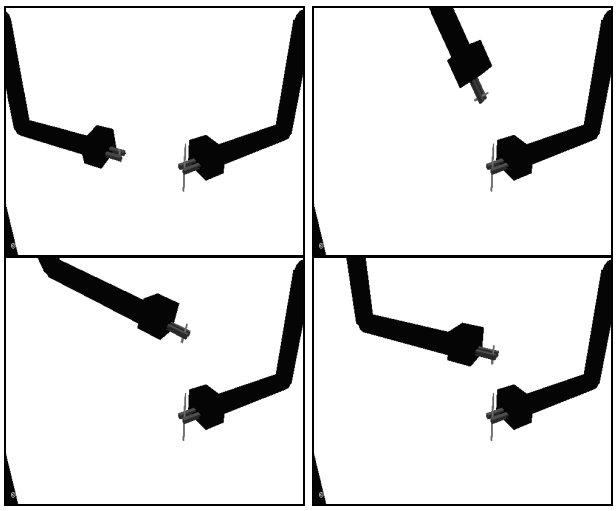


Figure 1: Pen recap by coordinated visual servoing

Multicriteria visual servoing

RAP will continue to study LMI-based approaches to visual servoing. In this not classical approach on robot control, two kinds of prospects can be exhibited. On the one hand, short-term incremental developments will concern an evaluation of the multicriteria analysis method on more complex case studies, and its extension to other types of Lyapunov functions, e.g. polyquadratic or homogeneous polynomial Lyapunov functions. Multicriteria synthesis will be considered as well. Actuators saturations will be tolerated rather than avoided, which is meaningful in a kinematic context. Last, the recently developed approach to set-membership filtering of nonlinear rational systems will be assessed on the visual localization problem stated as the dual of visual servoing.

On the other hand, more fundamental mean-term objectives are twofold. On a Control Theory aspect, more efficient relaxations will be envisaged so as to get less conservative LMI conditions. On the Robotics side, the aim will be to "bridge the gap" between the suggested approach and existing developments in visual servoing. For instance, other visual features will be inspected, so as to isolate the ones that lead to a better conditioning of the problem. The aim is to limit the conservativeness of the conclusions so that an LMI analysis or synthesis strategy can provide an answer to difficult robotics problems.

A subset of these prospects constitute the subject of a STIC-AmSud project, which has recently been applied for with Prof. Daniel F. Coutinho (PUCRS, Porto Alegre, Brazil), Prof. Luís A. Pereira (UFRGS, Porto Alegre, Brazil), and Prof. Miguel Torres-Torriti (PUC Chile, Santiago, Chile).

Sensor integration

Algorithm-Architecture Adequation in Robotics is mainly concerned with the design and the development of smart sensors, i.e. adapt algorithms in order to be executed on dedicated hardware in the sensor. There exists products (dense stereovision at 30Hz, visual tracking of interest points or of blobs …) and the technology is evolving every day. Robots or vehicles are merged in unknown or cluttered environments: for SLAM or visual servoing based on feature tracking, for the obstacle avoidance that relies on a detection method, faster are image processing and interpretation, more robust and reliable are functions.

So real time processing of sensory data is fundamental in robotics. But, this topics could be seen as too technological if objectives are not ambitious. During the last period our aim has been a 100Hz dense stereovision sensor (LAAS project PICAS$O, with MRS and N2IS) : the final result was not convincing, but we learnt a lot. The on-going project is an Obstacle Detection sensor, using 8 micro-cameras mounted as a belt around a robot. In the next period, these prototypes will be improved.

Two new projects are beginning in which integration is required : CameraNet (Region, 2009-2012) intends to build a visual monitoring system of large environments, as a wireless network of smart cameras. SART (FUI, 2009-2012) intends to design and develop the prototype of an autonomous multi-spectral visual sensor to be integrated on an airplane, for obstacle detection when navigating on taxiways. Some extensions of this project could concern airport cartography, airplane localization, pilot assistance …

Others

As it is done by now with ORME, DTSO, NAVONTIME and NOOMEO, the RAP group will remain available for more focused or applicative research works, in collaboration with local SMEs or in the context of CIFRE projects, For example a new project about localization will begin December 2009 with the CLS company (*Collecte Localisation Satellites*)

Robotics and InteractionS – RIS –

Context and Challenges

RIS will pursue its efforts towards the development of models, algorithms and paradigms for autonomous decision in dynamic environments.

This endeavor will be nurtured by the two complementary perspectives that have been set up in the last reporting period: the fundamental perspective and the contextual one. The new challenges on which we will concentrate and that we think are now essential to the robotics domains, are (1) facing and dealing complexity on one hand and (2) the need to deal with real environments with far more refined and pertinent models and algorithms, on the other hand.

For this second aspect, our challenges for the next period can be summarized as:

- Toward a principled approach to design, build and deploy a companion robot with an illustrative focus on fluent, acceptable and highly adaptative human-robot interaction abilities. The main focus will be the decision-making mechanisms that are induced by the demanding context of scenarios for a personal robot where a robot has to effectively manipulate objects in cooperation with humans and/or for assisting them.
- Toward a principled approach to design, build and deploy a set of cooperative robots in unstructured environments. The main focus here will be a general framework for solving environment modeling and monitoring problems expressed as a global mission to a set of networked heterogeneous robots under dynamic constraints.
- Toward a principled approach to model and simulate molecular motions and interactions, to help in the long-term better understanding of the molecular machinery. The main focus will be the development of high-performance, atomic resolution, simulation techniques able to tackle the important challenges of structural biology and of novel nanoscience technologies.

The first two challenges are aimed to converge into a "theory" for robot interaction based on common paradigms, models and software tools.

We will also seek to apply and contextualize what has been already developed in relation with industrial partners: human-robot cooperative work applied to assembly tasks, development of assistant robot in specific professional or domestic contexts, deployment of multi-robot systems for surveillance, monitoring and intervention tasks.

All these activities will be conducted in strong relation with LAAS research teams within the Robotics and Artificial Intelligence areas. Based on this, RIS will be naturally involved in the two main strategic topics defined at the laboratory level: the ADREAM initiative and the interaction between life and systems.

Another dimension is the need and the will to enforce considerably long-term scientific cooperation and coordination with the best research teams within a strong multi-disciplinary approach that we feel mandatory in order to capture the richness of the applications that we envisage.

Elements for a SWOT Analysis

We have conducted a SWOT analysis of our group, which we summarize here below:

Strengths: a solid visibility in the domains put forward by the group and a good coherence and complementarily between its researchers. The group has already proved and is working to enhance its ability to conduct ambitious projects.

Weaknesses: heavy load on the shoulders of the permanent staff. Engineering support too low with respect to our experimental needs. A spectrum of domains that might seem too large and the urgent need to re-enforce the permanent research staff. For the time being, the team is essentially re-enforced through postdocs.

Opportunities: the group is in an ascendant situation where a number of results are expected, linked to current and planned projects. There is also a large opportunity to take full benefit from strategic alliance with other French or European research teams: AEROS Lab with ONERA, VERIMAG, TU Munich.

Prospective equipment and research framework is also positive: new robots will be deployed for both experimental contexts as well as an experimental site linked to the ADREAM ambient intelligence LAAS initiative.

Threats: the risk of resorting to multiple and short-term projects due to the potential difficulty to obtain a sufficient financial support for a small number of large and long-term projects. For instance, robotics is today broken up in several ANR programs. Another potential threat is the small number of local industrial partners interested in autonomous robotics.

Major research orientations and projects

Control Architectures, Planning, learning

One of our long-term goals is to provide an architecture and a set of tools to develop a complete autonomous system with validated and verifiable properties over the whole system and software. In the coming years, we plan to merge the "Robust and Dependable Architecture for Autonomous Robots" and "Temporal Planning and Execution Control" themes. Indeed, we propose an evolution of the BIP-LAAS approach toward the decisional level. Currently, we are able to synthesize a BIP model of the complete functional layer of the architecture. Our goal is to move upward and propose a similar model of the planning and plan execution control/supervision components. Note that it is not clear at this stage if the produced model will be used the same way it is at the functional level (i.e. with the BIP engine controlling the execution of all the components, and the code executed for each transition). Still, we think that the produced model could be used to:

- Control and guide the search which elaborates plans (this could be based on mechanisms similar to the one we investigated when using UPPAAL TIGA as a temporal planner),
- Check if some formal properties are satisfied or not in the planning/execution model (using tools like D-Finder developed by VERIMAG).

In any case, being able to use a consistent model and approach through the entire architecture will ease the checking of properties which span over more than one level (functional and decisional). This research will be conducted within the GAEAI project (ESA).

"**Learning skills, modalities and plans"** — Another long-term goal is to have a robot which learns skills, operational procedures and plans. This can be done by having the robot to experiment by itself, to learn by watching and observing a human teacher, etc. We plan to extend the DBN approach deployed so far to endow a robot with the ability to learn to improve its behaviors and activities. So far, we have successfully applied our DBN/DDN approach to improve the control parameters of a "black box" controller for a simple navigation task. We plan to apply it to other simple behavior (such as approaching objects, grasping them, handling them to humans, etc), but we also want to study how different learned activities can be combined (using some plan execution controller) and if we can learn a better way to combine them (again by learning a more abstract DBN of the complex activity or the proper parameters of the higher plan being executed).

More generally we will investigate schemes based on the utilization of skills and plans learned or explored off-line. Here the challenge is to come up with an architecture and with the relevant methods that will allow a robot to select the relevant plan from a plan repository, that has been updated off-line or based on previous experiences, and to adapt it to the current situation.

"Bridging the gap between symbolic and geometric reasoning" — Another main challenge is to devise a formal way to link in a rigorous way symbolic and geometric reasoning. This is a key aspect to effectively open the path to use high-level planners in non-trivial robotics tasks.

Preliminary work on the Asymov planner and on perspective planning were a first contribution to allow a far more elaborate interaction between symbolic and geometric reasoning. We will pursue and extend this research and study how both decisional processes can be conducted in parallel and can both contribute to the selection, instantiation and articulation of various robot primitives.

This is also linked to the issue of grounding the internal information used by the robot for its actions and perceptions to abstract concepts that can be dealt with in an ontology that can be used to describe human and robot behaviors and objects of interest. This could allow more natural interaction and even build an understanding of underspecified action commands by the human.

Motion and manipulation planning

Future work remains strongly anchored on the development of novel algorithms to address yet unsolved problems in robot motion planning for complex manipulation tasks with complex multi-arm systems.

"Robot motions" — Despite the recent progress of the domain, a deeper integration of planning, reaction and control remains yet a challenge for advanced action capabilities, with interesting issues for motion planning to be investigated further. In particular, motions for complex robot systems such as humanoid torso and complex manipulation tasks in real-world settings are still a challenge, specially in the context of human-robot collaborative tasks: state of the art planners are yet insufficiently reactive and motion plans are fragile with respect to contingencies. Thus, we aim to develop novel approaches, that incrementally produce deformable and reusable motion plans and investigate new reactive schemes that are able to select and adapt on-line the relevant motion plans. This research will be conducted in the frame of the two EC projects (DEXMART, CHRIS) dealing with robot manipulation.

"Robot object manipulation" — It is today largely accepted that one main challenge of robotics is now oriented toward autonomous object manipulation. We fully share this view and plan to contribute in the context of dual hand-arm dexterous manipulations performed interactively with humans. Besides motion planning, discussed above, we will extend our work on grasp planning (including multi-fingered hands) as well as on the synthesis of trajectories with safe, comfortable and legible dynamics ("soft" motion generation). Another complementary aspect is the study and the elaboration of models including several modalities and constraints (vision, force, contact, time) that will allow a robot to efficiently act in coordination with humans. One very illustrative example is the action of handing an object to a person. This work will be essentially developed in the framework of two projects: DEXMART (IP-FP7) and French ASSIST (ANR, PSIROB).

Environment modeling

We will pursue our activities on environment modeling in the context of field robotics, aiming at building and maintaining a large-scale multi-purpose composite environment model, using all the available sources of information.

The application context of these activities is the deployment of a fleet of heterogeneous robots. Within such a system, information related to the environment is at the heart of the robots autonomy and of their cooperation schemes. It is indeed required for a large variety of tasks: to set goals to reach, to plan motions, to assess the feasibility of perception or communication tasks, to localize the robots, etc. As a consequence, the overall environment model is a multi-layered composite structure, each layer containing the information dedicated to a given process (*e.g.* a digital terrain model is exploited to plan rover trajectories, a volumetric 3D model is exploited to plan perception and communication tasks, a landmark model is devoted to the robot localization, etc). Our goal is to endow a multi-robot system with the ability to build and maintain such a model, and to provide the necessary functions to update it on the one hand, but also to exploit it for the purpose of the robot fleet operational needs. In that sense, we aim at developing a Geographic Information System (GIS) dedicated to robotics, using a large variety of information sources: the on-board robot sensors (vision in its various modalities, monocular, binocular and panoramic, Lidar and probably radars), but also initial information as provided by an existing standard GIS.

Two essential properties must permanently be maintained within such a system: its spatial consistency, and its symbolic (or semantic) consistency. Stochastic processes naturally constitute the core of the work on these issues.

Spatial consistency is ensured by simultaneous localization and mapping processes (SLAM). In a multi-sensory and multi-platform context, these processes are distributed among the robots, and landmark models must be rich enough to allow their associations among the robots. Geometry plays here an essential role, and we will pursue the extraction, modeling and matching of structured geometric landmark models. The multi-robot hierarchical SLAM approach we have recently developed will be exploited to maintain the spatial consistency of the model.

Besides geometry, the environment model must also exhibit relevant information to be exploited by decisional processes. We will focus on the development of processes that allow the extraction of semantic information from the acquired data and the a priori existing information. Information fusion processes will play here a central role: they can be applied to fuse data acquired by different robots and different vehicles, but also to mix the information scattered in the various layers of the environment model.

Toward a principled approach to design, build and deploy a set of networked cooperative robots in unstructured environments

The future of robotics will definitely reside in multi-robot systems that exhibit a better robustness in most of the application contexts. While multi-robot cooperation can also be studied in the framework of service robotics, we especially set the focus on distributed systems in the context of field robotics, considering in particular heterogeneous robots, *e.g.* systems composed of aerial vehicles and ground rovers, or of surface and submarine robots. Within such systems, we have the ambition to tackle the decision-making issues in a wholesome and integrated manner, by defining not only dedicated processes, but also an overall system architecture. We recently initiated four PhD theses in this area that consider various aspects of the problem.

Figure 1: Manta, the new LAAS UAV

Mission planning and management centered on task allocation processes: task allocation is an essential

decisional activity in multi-robot systems that sets the distribution of the tasks achievement among the available robots. We are currently revising previous contributions in the area, and extending them to more complex missions, in which the set of tasks to achieve is not a priori known: task planning (or decomposition) must therefore be handled incrementally and jointly with task allocation. Furthermore, we explicitly consider communications as tasks that must be planned, in order either to satisfy communication requirements specified in the mission, or to share information among robots. In the latter case, environment models and the model of information gathering functions are exploited to trigger communications among the robots. Research on this topic relies on the extension of a negotiation-based architecture, the main advantage of such an approach being that is handles online plan repair as well as mission planning.

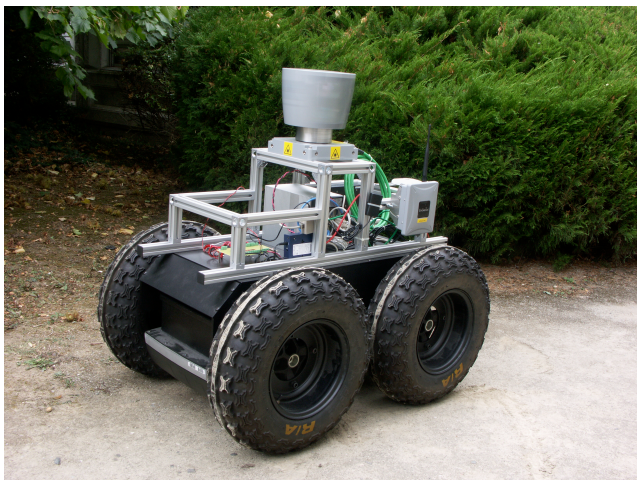


Figure 2: MANA the new outdoors mobile robot

Decision theoretic planning: most field robotics missions are information-gathering missions, e.g. to explore a given area, detect targets or environment modifications. The models of the environment and of the robot perception tasks play a central role in such missions, and their stochastic nature naturally leads to the consideration of a decision theoretic framework to deal with the robots actions -- these actions being motions, perceptions and communications.

Toward a principled approach to design, build and deploy a companion robot

One very challenging context for Human-Robot Interaction (HRI) is a robot that shares space with a person and that is able to cooperate by participating to a manipulation task. This has a great influence in terms of the main aspects to be dealt with at the decisional level. Indeed, it raises several very interesting and challenging issues:

- The ability of the robot to conduct intricate human-robot cooperation in a common space and the need to do this in a natural manner with respect to the person,
- The importance of contingency and uncertainties (from the robot point of view) due to the presence of the person,
- The interplay of symbolic reasoning and geometrical reasoning.

We will focus our investigations on the design of a conceptual architecture of the decisional component of a robot companion that acts, learns and interacts with humans. This architecture is aimed to be a framework that provides a basis for a principled way to deal with robot task achievement in presence of humans or in synergy with humans.

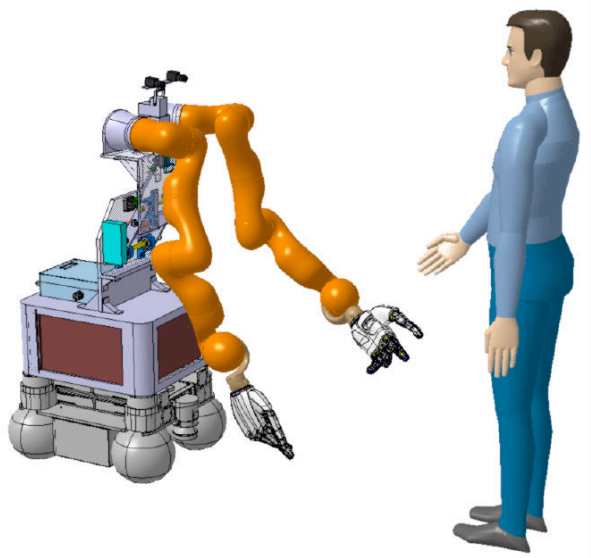


Figure 3: Sketch of an interactive robot with advanced manipulation abilities

As mentioned above, we plan to refine, through multi-disciplinary work, the categorization, the models and the articulation between the different abilities that should be available at the robot level. This will cover a large set of abilities from shared attention and intention reading to more active and proactive abilities such as shared goals and intentions and intentional behavior. Of interest are also questions linked to multimodal dialog that supports these activities. Other questions are linked, more generally to the underlying motivations and how they could be linked to the construction, at the level of the robot of initiative taking.

Toward a principled approach to model and simulation molecular motions and interactions

Research will be focused according to two main directions. The first research line corresponds to the continuation of our current work on simulating bio-molecular motions and interactions for structural bioinformatics. Besides, we will also initiate a novel research direction on molecular modeling problems to be explored for the field of nano material science.

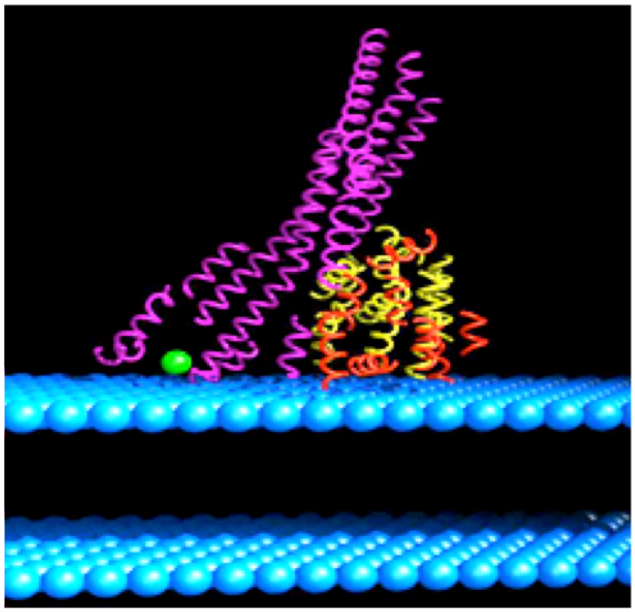


Figure 4: Protein-surface adsorption

"Structural bioinformatics"— Integrating macro-molecular flexibility in receptor-ligand interactions is of primary importance for accurate computer-aided drug design, but it remains yet a challenge for computational methods. Building on our recent results, we will further extend the techniques to better handle global molecular flexibility. We also aim to take advantage of the algorithmic performance of the approach to investigate novel virtual screening techniques of interest to biologists for the in-silico design of optimized enzymes. This research will be done in the frame of the ANR GLUCODESIGN project (2009-2011, Institut Pasteur, LISBP, LAAS). Besides, we will also investigate the extension of our conformational search algorithms to flexible macromolecular docking and macromolecular (dis)assembly problems.

"Simulation for nanoscience" — Besides structural biology, we will investigate the specific adaptations of the techniques for modeling at the atomic level the interactions between bio-molecules and solid surfaces (organic or not) involved in the construction of new functional nanomaterials, with applications in nanotechnology and medicine. In-silico design of bio-molecules with high affinity for binding solid surfaces is yet an unexplored research domain. Such problems will be first investigated in collaboration with the N2IS group in the frame of a co-advised PhD thesis (2009-2012) founded by the LAAS OTIMASU project. Also, nano-structured materials can be constructed using natural properties of bio-molecules (e.g. peptides, ADN fragments) that self-assemble, forming geometrically regular structures. Understanding the mechanisms and conditions that control such self-assemblies would permit to devise processes for synthesizing *ad hoc* nanometric objects.

Integrated within a multi-scale multidisciplinary approach, “robotic” algorithms may help to gain insights into this challenging but yet unexplored domain.

List of new or recent projects

Here below is a non-exhaustive list of project that we will conduct in the next period:

- DEXTMART - IP - FP7 (Feb. 2008 - Feb. 2012) Dexterous manipulation - Human aware motion
- CHRIS - STREP - FP7 (Mar. 2008 - Mar. 2012) - HRI - Cognitive architecture - Manipulation
- ACTION PEA-DGA (Jan. 2007 - Jan. 2014) - Control Architectures - Multi-robot cooperation - Perception and Environment Modeling
- MARAE - FRAE (Jan. 2008 - Jan. 2011) - Architecture - Validation - Planning
- SCA2RS - FRAE (Jan. 2008 - Jan. 2011) - Control Architectures - Multi-robot cooperation
- FAST (Feb. 2008 - Feb. 2011) - Perception - Perception - Environment modeling - Navigation
- AMORCES - ANR (Jan. 2008 - Jan. 2011) - HRI Cognitive architecture - Manipulation
- ASSIST - ANR (Feb. 2008 - Feb. 2012) - RAP - Manipulation with two arms - HRI
- GLUCODESIGN - ANR (Jul. 2009 - Jul. 2012) bioinformatics - molecular motion
- ROSACES - RTRA (Jan. 2008 - Jan. 2012) - coordinator - Networked multi-robot systems
- GAEIA - ESA (Sept. 2009 - Sept. 2011) - Architecture - Validation - Planning

Research domain
Critical Information Systems – SINC –

As identified by the groups of this research area, mobility, evolvability, openness, heterogeneity, autonomy, synchronization, adaptability, resilience, scalability, are a few of the key challenges and properties that are to be addressed and fulfilled by the investigations that will be conducted in the coming years.

The efforts towards the development of synergies among the research groups (e.g., characterization of attacks on the Internet, privacy preserving authorization schemes, formal methods and testing, etc.) will be pursued and developed further. In addition, periodic seminars and topical workshops are instrumental to strengthen these interactions.

It is also worth mentioning the trend towards increasing the interactions that exist with other research areas. In that respect, let us note: a) the continuing joint work carried out with the RIS group on the control and assessment of the robustness of the behavior of autonomous robots, b) the on-going cooperation with the MINC group for the development of protocols suitable to support the communication requirements in ad hoc sensor networks deployed in critical embedded systems, c) the joint work carried out with the N2IS group on the application of System Engineering methods to the design of microsystems and SoCs.

Three senior members from the LATTIS laboratory will integrate groups of the SINC area: one will join the TSF group (in particular, extending the work on fault prevention to address language-induced software faults) and two will integrate the ISI group (this is a natural consequence of the joint work already developed in collaborative projects and this will also contribute to further the above mentioned link with the N2IS group).

The leading role of the SINC groups in shaping the ADREAM program will drive the identification of and contribution to the innovative projects — on mobility, geolocation, ad hoc networking, vehicular robots, verification and simulation, etc., — that will be launched in that context. It is expected that the new building hosting ADREAM will constitute a privileged frame to nurture such projects that are spanning other research areas of the laboratory.

The long term privileged collaboration developed with Airbus in our research area within the AIRSYS convention has also contributed to underpin the interactions among the research groups within the laboratory, as well as with colleagues from IRIT and ONERA. Opportunities to extend such a form of close and recurring cooperation framework to other industrial partners are being investigated.

Tools and Software for Communication – OLC –

Context and Challenges

Since 2000, OLC is structured around three research axis (FDT: Formal Description Techniques, APC: Communication, Architectures and Protocols and CSC: Services and Components for Cooperation). From then, 8 new researchers joined the group and 4 left (2 retirements and 2 delegations). This dynamic made possible to reinforce the existing research themes and to explore new directions.

Evolution and convergence of the fields of software architectures, networks and communication protocols, on one hand, and of adaptability, reconfiguration, measurement and communication techniques (for both wired and wireless technologies), on the other hand, leads now the APC and CSC axis to be merged.

Furthermore, this merge, centered around cooperative and embedded autonomous communication, fits well into the objectives of the federating project ADREAM ("Architectures Dynamiques de Réseaux Embarqués Autonomes Mobiles"). This new local context will reinforce the present internal synergy in our group and will allow us to consider new collaborations with the other groups of LAAS, namely in robotics and energy-related applications.

The FDT axis continued its investment in the field of modeling and model-checking real-time critical systems, in the development of the supporting tools and in the integration of the formal techniques in industrial processes. Although the applicative context was primarly directed towards hard real-time and avionic applications, a few new applications targeted by ADREAM constitute an opportunity for the group for applying again the formal approaches for embedded communicating systems design.

The work developed over the past period and now planned belongs to the research programs of AIRSYS, of the French "competitiveness cluster" Aerospace Valley and of STAE/RTRA as well as of national and European research programs (FP7, ARTEMIS, …)

For the next period, the OLC group will be organized around two research axis: "Verification of Time Critical Systems", and "Advanced services for autonomous networks", detailed below.

Major research orientations and projects

Verification of Time Critical Systems

The research is focused on techniques for the description and formal verification of time critical software systems. Our contributions in this domain are at different levels and target languages, methods and tools. More particularly, we develop formal models for describing real-time systems; we work with logics for expressing their properties; we define and implement verification techniques and algorithms for validating them.

We detail a list of topics that structure our previous and future works.

"Qualitative and Temporal Analysis" — The problems addressed here is how to specify the behavior of real-time software and check whether a system meets its specification. We are interested by qualitative properties (absence of deadlocks, liveness, potential/eventual occurrences of events or of a system configuration, etc.) as well as timed properties (worst case execution time, timed sharing constraints for resources, etc).

This line of research extends early works undertaken in the OLC group that lead to the development of tools like TINA (http://www.laas.fr/tina/) and POLA, and of their underlying analysis techniques. Our last investigations in this area are concerned with scheduled systems and the verification of qualitative and timed properties following an observer-based approach and the use of model-checking techniques.

Future work will address the model-checking of timed temporal logics and verification techniques supporting dynamic priorities in scheduled systems.

The goals and approaches described in this section are shared by a number of international projects like UPPAAL/TIMES (Uppsala/Aalborg), ROMEO (Nantes) or ORIS (Florence).

"Quantitative Analysis" — The uncertainty of time information associated with the actions of a system can be interpreted stochastically rather than as behavioral non-determinism. In this case, the problems we want to tackle are of a probabilistic nature: is the behavior of the system statistically correct (including temporal aspects)? What are the probabilities of occurrences of incorrect states? etc. Such problems have been addressed in the past by the OLC group taking an approach based on Stochastic Time Petri nets. We plan to enrich these results by developing model-checking techniques for this kind

of models. This will take the form of specific modules, grafted to our current tools (TINA), to perform stochastic analyses and to combine verification and performance analysis. Prospective work include verification of probabilistic systems (logics and algorithms) and performance analysis of timed systems. Prominent projects in this domain include, among others, GreatSPN (Turin, Stochastic Petri nets) and the PRISM model-checker (Oxford, probabilistic systems).

"Integration of Formal Techniques into Actual Development Processes" — A major difficulty for a wide acceptance of formal methods in industry is the significant investment required to master the necessary formalisms and methods. The goals of this line of research are to ease the use of formal methods and their integration within actual industrial design processes. To shorten the distance between formal and pragmatic methods, a common strategy is to semantically connect semi-formal notations, like UML for instance, with some formal language enabling verification. The work around the intermediate language FIACRE (definition of a formal semantics, backend compiler to TINA) contributes to this goal. A series of experiments have been conducted in the context of projects like TOPCASED (FUI&CRMIP), SPICES (ITEA2) and OpenEmbeDD (ANR) and lead to the development of a full verification tool-chain for AADL, the SAE Architecture Analysis and Design Language.

Figure 1 illustrates more directly our current and future activities around the language (FIACRE) and tools (the frac and flac compilers, the TINA verification platform) developed in our group. The figure also depicts the context surrounding our work. For instance the interfacing of our verification tool-chain with other modeling language and verification platforms. These activities will contribute to projects that have started in 2009 [Cesar, Quarteft, Itemis]. Along with these projects, our efforts are also supported by longer lasting structures, namely the Aerospace Valley competitiveness cluster and Airsys.

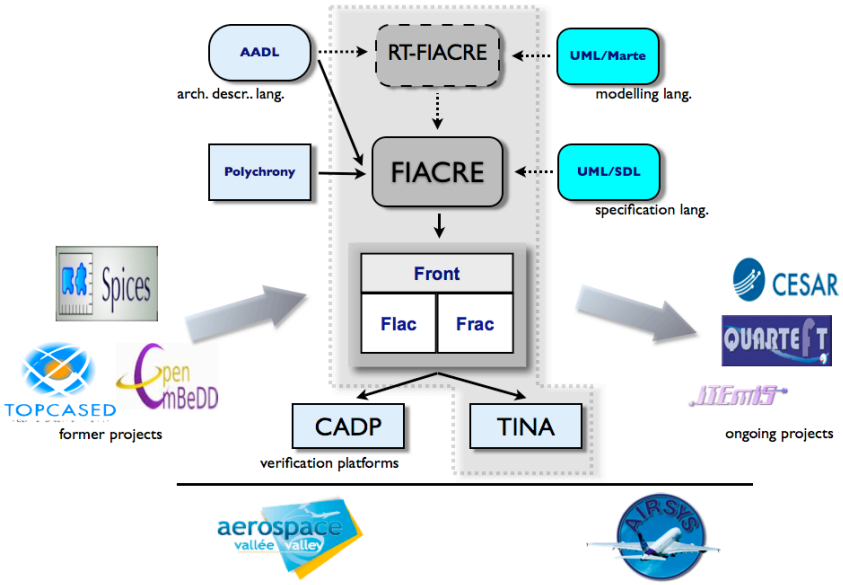


Fig. 1: Activities around the FIACRE language

In this context, future works will address: the expression of "domain specific properties" suitable for expressing the correctness of particular domains of applications; the interpretation of verification results into a user-friendly formalism (rather than its translation into the verification formalism); extension of the FIACRE language with real-time constructs (RT-FIACRE) and the certification/qualification of the verification chain (an important concern in some application areas).

"Improving the scalability of verification methods" — The use of verification techniques for "real-world" applications requires to improve the scalability of our verification techniques and tools. A major challenge for verifying industrial applications follows from the "combinatorial explosion" problem, because the state spaces of the formal models to be analyzed can grow exponentially in function of their complexity and could therefore be too big for enabling analysis. Several original techniques (partial order techniques, use of symmetries, geometric abstractions, etc.) have been used and/or developed in the OLC group to obtain state space abstractions for (timed or untimed) systems allowing the verification of specific families of properties. The results are promising, but scalability of verification techniques remains a long-range research topic.

In this context, we plan to investigate parallelization of model-checking verification techniques, cooperation of abstract interpretation techniques (static analyses) with model-checking, and compositional verification methods.

"Handling continuous data" — The objective, in this last topic, is to extend the class of models and verification problems currently addressed to those involving continuous (dense) data. A number of such models have been proposed, including Linear Hybrid Automata and various Hybrid extensions of Petri Nets. Nonetheless, these models remain seldom used, which may be attributed to the fact that most verification problems for such hybrid systems are undecidable.

Proposed works will attempt to develop methods for subclasses of hybrid systems obeying two constraints: (1) they should be expressive enough for practical purposes and (2) the interesting properties of such systems should either be decidable, or could be addressed by adequate and efficient approximation techniques.

Advanced Services for Autonomous Networks

The prospective of this axis for the next period includes studying the communication architectures, protocols and services for the cooperative, heterogeneous, dynamic and complex networks and their applications. We will continue our efforts on the analysis, the design, the prototyping and the experimental evaluation, and on the development of specific methods, models, tools, software and platforms. The scope of the future studies will include heterogeneous wired and wireless networks, with infrastructure or ad hoc, of type Internet or more specific according to the constraints of the considered application domains: embedded systems, distributed, mobile, cooperative, ubiquitous and critical. Two axes will be studied thoroughly considering evolving application properties and requirements (mobility, cooperation, ubiquity, criticality, quality of service, safety…) and changing environment constraints (time, distribution, energy, …)

The first axis addresses the adaptive communication architectures, protocols and services for dynamic reconfiguration with a particular focus for its application for managing complex requirements of Quality of service and Security.

The second axis addresses the communication architectures, protocols and systems with guarantee of service for strongly constrained applications.

The following research topics will be investigated:

"Autonomous communication architectures" — On the one hand we will address networks that are strongly constrained by the requirements of various critical applications including:

- "Real-time" Applications: sensors networks for measurement, interconnection of real-time simulators …
- Applications of the field of the "Automatic": network control and network-based control.

On the other hand we will address the heterogeneous, potentially dynamic networks, and their interconnection, for the support of the cooperative and mobile embedded applications including:

- Ubiquitous applications and
- Mobile and embedded cooperative applications

Observation and Analysis

This axis addresses observation and analysis of the traffic and the interactions on the various levels of communication (network, transport and middleware). This includes the development of tools for metrology, tools for analysis and measurement of quality of service for detecting, identifying and anticipating the dysfunctions of the communicating system and the traffic anomalies (of type of denial-of-services, sudden crowd, …) and the associated degradation of QoS.

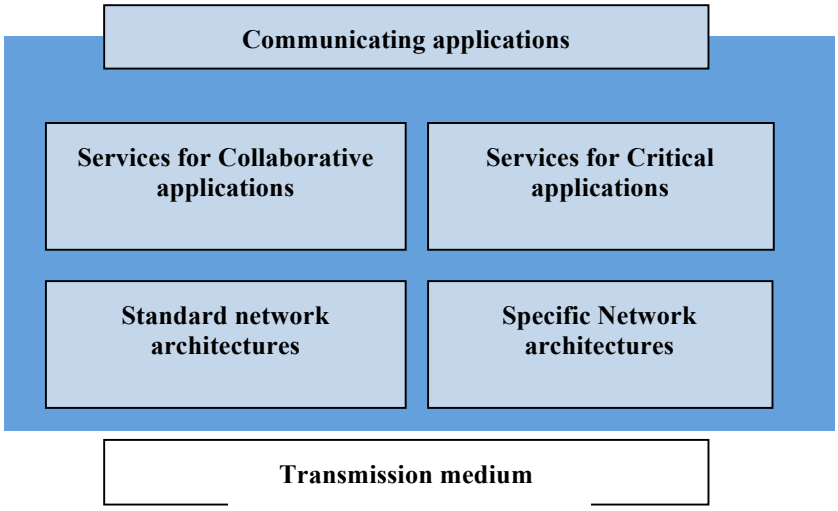


Fig. 2 : scope of contributions

Dynamic reconfiguration

This work will consider the design and the implementation of software environments for the support of behavioral and architectural reconfigurations for mono and multilevel, dynamic, autonomous, and co-operative adaptation of the communication services and protocols.

On one hand this includes the specification and the enforcement of adaptation policies based on architectural, behavioral and semantic models to control the complexity inherent to the heterogeneity and the distribution and able to guarantee, when necessary, the scalability.

On the other hand, this includes prototyping supports for the deployment and the execution of services at various levels of communication.

Advanced Communication protocols and services

This study will address the design and the implementation of advanced communication protocols and services working either in an adaptive or a guaranteed mode for ensuring in particular:

- "localization" for maintaining the connectivity, optimizing the routing for embedded and ad hoc networks,
- tolerating the delay and disconnection, as in the satellite or vehicular networks,
- "controling the needed energy".

Experimental platforms

We will continue and extend our effort related to the experimental platforms functioning in simulation, emulation or real mode, this last mode being obtained by the integration of various prototypes constructed in the OLC group.

Green Networks

This work will address designing "green networks". Nowadays networks consist of millions of components and devices that are consuming energy 24 hours a day, 7 days a week. In addition, the evolution of wireless communications causes the generation of always more electromagnetic waves, and the growing importance of the Internet could badly impact our environment. In the framework of the ADREAM project, the design of green networks will be addressed for a healthy and sustainable development.

Associated Projects

[IMAP] Information Management for Avionics Platform, DGAC - 04/2009 – 06/2011 (39 mois),

[A2NETS] Autonomic Services in M2M Networks. ITEA2, 09/2010-11/2013 (Submitted for 10/2009 Call)

[AMIC-TCP] Architecture de Multiplexage Informatique et Communication dans les Transports en Commun de Personnes, OSEO 07/2009-07/2012 (36 mois).

[CESAR] - Cost-efficient methods and processes for safety relevant embedded systems 03/2009 3 ans ARTEMIS/JU http://www.cesarproject.eu

[QUARTEFT] Langages intermédiaires et technologies de transformations qualifiables pour le développement de systèmes temps-réel
05/2009 3 ans FNRAE http://quarteft.loria.fr/

[ITEMIS] IT and Embedded Integrated Systems
01/2009 3 ans ANR/Arpege http://itemis-anr.org/

[MOOSE] - Management and Operations Solutions for the Future Internet, Network of excellence (proposal to be Submitted in October 2009) - 48 mois

Dependable Computing and Fault Tolerance – TSF –

Context and Challenges

The computing systems of interest to us are the large, networked, evolving systems of the future, interconnecting servers, mobile computers, and embedded devices to form complex information infrastructures. The major issue at stake in such *ubiquitous systems* is how to maintain their dependability, i.e., their ability to deliver service that can justifiably be trusted, in spite of continuous change. The changes to which ubiquitous systems are subjected can be functional, technological, or environmental, and may include or induce new threats.

In this context, our research is best situated in the context of *resilience*, i.e., the persistence of dependability in the face of change.

A thorough analysis of the research challenges of the future resilient ubiquitous systems, taking into account both our expertise and the likely applications of our work, led us to identify four major challenges: *mobility*, *evolvability and autonomy*, *openness*, and *reactivity*. We will address these challenges from two complementary, and closely related, viewpoints:

- *Architecture*: design approaches, policies, algorithms, and mechanisms, for fault prevention and fault tolerance.
- *Analysis*: verification and evaluation techniques for fault removal and fault forecasting.

Major research orientations and projects

The table below presents our prospective research topics, structured according to the four identified challenges, and to the architecture and analysis viewpoints. We have recently begun to investigate some of these topics, and plan to pursue them in more depth. Other topics, shown in italics in the table, are entirely new research directions that are yet to be explored.

Mobility

Mobility has both negative and positive facets. On the negative side, mobility introduces new threats (e.g., sparse connectivity, wireless communication eavesdropping). On the positive side, the related notion of locality, when handled correctly, can be beneficial to system design. Both facets of mobility need to be studied in the context of resilient ubiquitous systems.

Architecture

"Geoprivacy" — Emerging ubiquitous applications generally imply the use of geo-located devices (e.g., cell-phones, vehicles) that are aware of their physical location. These objects are often personal devices, so learning their location usually implicitly discloses the location of their owner. Of the various sorts of personal data whose collection can be a threat to privacy, location information is one of the most sensitive: it can help to trace a person, to identify that person's interests or to detect an unusual behavior. It is thus crucial to protect the past, current and future locations of an individual from disclosure (except by explicit consent of the person concerned).

	Challenges			
	Mobility	Evolvability and autonomy	Openness	Reactivity
Architecture (Fault prevention and Fault tolerance)	*Geo-privacy* *Mobility-explicit computing models*	Self-organizing fault-tolerant nanochips Adaptability of fault tolerance software Defenses for autonomously-adapting systems	Privacy protection Operating system kernel protection Virtualization and diversification	Distributed online error detection Online reconfiguration Preventing language-induced software faults
Analysis (Fault removal and Fault forecasting)	Dependability evaluation in a mobile context Testing mobile settings	Risk analysis for autonomously-adapting systems Testing of autonomous system software *Testing of aspect-oriented software* *On-line evaluation of resilience*	Security metrics Characterization of attacks *Benchmarking security protection mechanisms*	Testing and formal verification of behavioral models *Search-based statistical testing*

One approach is to reduce location accuracy to reach an acceptable tradeoff between the utility of location-sensitive tasks and privacy protection. Some cryptographic techniques (e.g., secure multiparty computation) can also compute a global result depending on a large number of people without disclosing any information on particular individuals.
We will explore how such techniques and others can address the privacy problems raised by geo-location.

"Mobility-explicit computing models" — Mobility of user-carried devices combined with short-range wireless networking induces a fundamental shift from the traditional distributed system viewpoint: contrary to the Internet model that abstracts away location, systems of mobile users are tightly coupled with the geographic world. A major challenge is thus to provide formal computing models that provide a realistic and usable representation of user positions, device failures and connectivity. The computational counterpart to such models is the main challenge when dealing with mobility: the provision of a toolbox to ease the programming of these new systems. This toolbox will provide programmers with abstract building blocks such as storage, agreement and membership services. These building blocks will either take advantage of mobility, e.g., by providing localized services, or aim to hide the intrinsic complexity of system dynamics.
The interest of mobility-explicit computing models is twofold: first, they serve as a basis to provide formal proofs for resilience algorithms, and second, they may be used as inputs for dependability evaluation of mobile systems, as we shall see in the next section.

Analysis

"Dependability evaluation in a mobile context" — The mobility-explicit computing models will be used to define meaningful parameters such as infrastructure access rates, or specific failure rates, along with their associated distributions. We will integrate these parameters into our analytical evaluation approaches based on Petri nets or Markov chains to provide analytical dependability assessments that are pertinent in a mobile setting.
In addition to analytical evaluation, we plan to develop new *fault injection* techniques to analyze the behavior of mobile systems in the presence of faults. Two major difficulties need to be addressed: i) what new types of faults and failures are induced by mobility, and ii) how to inject faults in a mobile device or in a location-aware system. To address these difficulties, we recently began the development of a laboratory-scale platform to *experimentally evaluate* and validate resilience mechanisms of mobile ubiquitous systems. It scales the physical dimensions of a real-life mobile system into ones that are practical for experimentation in a laboratory environment. By changing scale, we plan to emulate systems of different sizes, from networks of communicating road vehicles, down to nanorobots injected into the blood systems to perform surgery. The platform will serve as the basis for the development of new fault injection tools and techniques.

"Testing mobile settings" — We recently proposed a scenario description language that captures mobility-related aspects at the system level along with the appropriate tool to automate the matching of test traces to these scenarios. This work will be extended towards validation of requirements in mobile settings. This requires realistic emulation of the mobile environment and controlled execution of the retained scenarios in a context-aware manner. This will necessitate the development of a test platform that integrates a network simulator and a context controller. Contextual parameters, such as memory and processing capacity, will be taken into account both at the level of the scenario language and in the test platform context controller.

Evolvability and autonomy

To deal with change, critical computer-based systems of the future need to exhibit a high degree of evolvability and autonomy. To this end, we need to develop new theories and methods for describing, designing and analyzing dependable self-organizing and self-adapting systems.

Architecture

"Self-organizing fault-tolerant nanochips" — This theme deals with the increasing critical problem of building dependable computing nano-architectures able to tolerate physical faults resulting from the reduction of dimensions down to the molecular level and to ensure system scalability in spite of increasing complexity. We believe that the only viable approach in the long term is that nanochips should be able to fully self-diagnose and to autonomously implement adaptative fault tolerance mechanisms in the physical layers. In the short term, we apply these ideas to nanoelectronics, in particular to the design of dependable general-purpose multicore chips, so that a general-purpose multicore chip becomes a black box that autonomously maintains its processing capabilities by tolerating manufacturing defects and transient runtime faults.

"Adaptability of fault tolerance software" — We plan to take advantage of novel software engineering techniques for implementing adaptability, self-healing and self-organization, based on open components, reflection, and aspect orientation. We are particularly interested in applying these techniques to dynamically adapt system defenses

according to changes in available resources, system configuration, operational environment and external threats. In this respect, our previous work on fine-grain adaptation will be continued. However, we also plan to address the evolvability of dependability defenses when the application software itself is engineered for evolvability using these techniques.

For dependability defenses to be able to evolve dynamically, an appealing field of investigation concerns methods for adapting defenses in a proactive manner, before any errors are detected or any failures occur. Anticipatory adaptation might be triggered in reaction to an on-line assessment of the system state and the environment to which it is subjected (e.g., workload).

"Defenses for autonomously-adapting systems" — The counterpart of autonomous adaptation for dependability is the confidence that can be placed on the underlying mechanisms. In particular, what defenses can be provided as countermeasures against the threats introduced by autonomous adaptation?
Several threats need to be considered: a level of adversity beyond the capability of the autonomous adaptation technique; lack of precision in the perception of the system state and environment; faults and other deficiencies in the design of autonomy mechanisms, such as heuristics or other design compromises introduced to allow computational tractability.
In the short term, our research on this theme will focus on the safety of autonomous robot systems based on the use of safety monitors. Different types of monitors can be used to provide multiple lines of defense: a) monitors that are physically independent of the main control channel; b) monitors intercepting interactions within the main control channel; c) high-level monitors capable of reasoning about the safety of long-term plans of autonomous action. A systematic approach to using such safety monitors requires methods and tools for identifying the safety rules to be checked, and the corresponding languages and safety monitor design patterns.

Analysis

"Risk analysis for autonomously-adapting systems" — Risk analysis is a prerequisite for the design and implementation of risk-reduction defenses. In the area of dynamic autonomously-adapting systems, especially those that interact physically with human beings (e.g., service robots), current risk analysis techniques (fault trees, failure modes and effects analysis, hazard operability (HAZOP), etc.) are quite limited and difficult to relate to the development process. We therefore intend to investigate which system behavior models and system-human interaction models are appropriate for early risk analysis of autonomously-adapting systems. In the short term, our research will build on our previous work on HAZOP analysis of human-robot interaction scenarios described with UML use case and sequence diagrams and will focus on tool support. In the longer term, we need to address human factor issues in more detail, since risks akin to mode confusion are exacerbated when humans interact with autonomously-adapting systems that appear to act as if they had minds of their own.

"Testing of autonomous system software" — The exploration capabilities of model-based decisional software, which provide the flexibility that autonomous systems (e.g., robots) require to operate for extended periods of time in an unknown and evolving environment, also make such software seem unpredictable to human eyes, both in terms of execution and verification. A small change to the domain model and the domain-specific search heuristics can have surprisingly dramatic changes in the decisional software's behavior, both in terms of accuracy and performance. Similarly, low-level reactive software of autonomous robots is designed for maximum runtime flexibility, allowing essentially infinite possibilities for interleaved calls to a set of multi-threaded asynchronous real-time functional modules. Defining and executing test cases able to provide a meaningful assessment of the adaptability and robustness of autonomous system software with respect to an unknown and dynamically changing environment is daunting and extremely time-costly. Building on experience gained from our previous work on testing fault-tolerant planners and current work on robustness testing of robot reactive layer software, we plan to explore two directions to facilitate such assessment: a) the combination of intensive simulation testing and analytical techniques (such as model-checking); b) massive parallelization of the simulation testing activity, using a grid-based environment.

"Testing of aspect-oriented software" — Aspect orientation is a major technology for implementing evolvable and adaptable software. It enables various forms of program specialization in a way that is orthogonal to the application program itself. Aspects are devoted to some non-functional code and synchronized with the application code through pointcut languages. Although this approach is sound and attractive, and probably the future of programming languages, testing aspect-oriented programs is a real challenge, especially for critical applications. Using well-established testing techniques, our objective is to develop testing strategies for such types of programs. We will consider, in particular: (a) verification modularity (incremental testing steps, exploiting former

verification steps), (b) probabilistic generation of tests based on structural or functional models, and (c) testing architectures enabling the target system to be controlled and observed. Ideally, we should be able to argue on the limits of using aspect-oriented programming regarding verification.

"On-line evaluation of resilience" — Proactive adaptation of system defenses necessitates on-line monitoring and evaluation to: (a) trigger a system adaptation once a discrepancy has been identified between the actual and the assumed/previously-measured resilience attributes or when changes in the operational environment have been detected, and (b) select the most appropriate adaptation and reconfiguration strategies.

To achieve these objectives, several challenges need to be addressed. A major difficulty is finding the right metrics that exhibit the best correlation with system failure events. As the systems evolve, so might the 'goodness' of the predictive metrics, hence a static selection of suitable metrics may be inappropriate. An operational assessment of the predictive power of the candidate metrics is needed. The development of efficient on-line monitoring and prediction mechanisms is also challenging due to observability and commandability constraints, including the need for rapid reaction as soon as an adaptation condition is triggered. In particular, the dependability evaluation models have to be built and processed on the fly, taking into consideration the fact that the faults affecting the system, and the system structure and behavior, are subject to evolution. Our objective is to develop new theories, models and tools that are well suited to address these challenges.

Openness

The need for interoperability with multiple systems and multiple stakeholders is fuelling a trend for increased openness, even for embedded systems. The attendant risks of malicious attack require architectures able to provide adequate protection and analysis techniques for assessing their effectiveness. Our work at the architecture level will focus on privacy protection, operating system protection and the use of virtualization and diversification for securing operating system kernels. From the analysis viewpoint, we will address the definition of security metrics, the characterization of attacks, and benchmarking of intrusion detection systems

Architecture

"Privacy protection" — A promising way to protect privacy is to enable individuals to manage different virtual identities for their relations with other parties, e.g., for different merchants, different services, etc. For each his identities, a person can select the best characteristics, in particular, its life-span (including single-use identities) and authentication strength. This is preferable to "single-sign-on" solutions and to remote identity management services (e.g., Liberty Alliance), over which the user has no direct control.

Another important research direction is to separate identification and authorization: a person should be able to prove his rights and privileges by means of anonymous credentials, i.e., without having to declare his identity. Cryptographic solutions exist, but they need to be applied to real-world problems. As an extreme example, we propose a "blank" national identity card, which would disclose no personal information about its owner, except by replying yes or no to specific questions (e.g., is the owner more than 18 years old, is he a French citizen, etc.). Such an identity card would be a contact-smartcard, with no personal information written on it (a blank plastic card, see Figure 1). Ownership of the card would be proven by the embedded chip using biometric authentication.

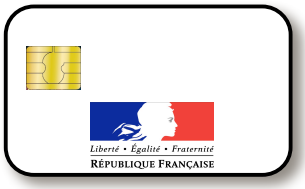


Figure 1: A blank national identity card

"Operating system kernel protection" — We will continue our investigations related to the use of trusted hardware-supported mechanisms. We plan to investigate, for instance:

- Protection of DMA input/output through the IOMMU chipset included in most recent PC architectures;
- Verification of kernel module loading using the Trusted Platform Module and the Intel Trusted Execution Technology.

Another short-term future work is to study to what extent our protection scheme can be adapted to the Windows environment (we have currently only developed a Linux implementation).

Our approach to protect operating system kernels is based on preserving some kernel constraints (the address of the system calls table for example, whose modification could lead to a loss of integrity of the kernel control flow). Up till now, these constraints have been identified manually. We plan to develop a formal model to represent interactions between the hardware platform and the various software layers (hypervisor, kernel and user space layers) so that these constraints can be expressed early on, at the same time as kernel specification.

"Virtualization and diversification" — The trend towards more open embedded systems targeting critical applications (e.g., avionics and automotive systems) via many kinds of communication networks (wired or not), including the Internet, results in cross-requirements that span both *safety* and *security* attributes. A comprehensive and consistent treatment is needed. Based on the insights gained in our previous work, virtualization and diversification constitute suitable approaches to tackle these issues in a cost-effective way. Nevertheless, several questions remain, including: (a) the synchronization of redundant entities run on a virtual machine, and (b) the level of confidence that can be achieved using such an approach, in particular when developers are faced with stringent certification requirements.
Concerning the latter, we also plan to develop an experimental framework for assessing the dependability and security of protection mechanisms with respect to both accidental and malicious faults. Indeed, to a large extent, the main related body of work has concentrated on attacks affecting applications deployed on the Internet (e.g., Web services or the like). The current corpus of results and research is much less advanced in the context of embedded systems, as fewer insights are available on attacks that might target such systems.

Analysis

"Definition of security metrics" — We plan to pursue the pioneering work undertaken years ago on the definition of security measures or metrics based on system behavior, as opposed to current measures, which are mostly indicators of the rigor of system development.
We will however significantly depart from our previous approaches. Those approaches were essentially probabilistic. If some phenomena involved in an attack of a system can indeed be modeled probabilistically, others are purely deterministic. We thus plan to establish mixed models, i.e., both probabilistic and deterministic, in order to derive measures meaningful for system developers, administrators, and users. In doing so, we will take advantage of the recent results we obtained on viewing system security as a combination of the vulnerability life cycle, attack profiles, and administrator behavior.

"Characterization of attacks" — Malicious attacks still raise several challenges concerning their characterization and the quantitative evaluation of their impact on the security of target systems and services. We will strengthen our activities in this context. First, we plan to extend the capabilities offered by our high-interaction honeypot for the observation and statistical analysis of real-life attack data. In particular, we aim to: (a) include a larger set of monitored vulnerabilities, and (b) consider a more representative target system composed of a large number of interconnected nodes, taking advantage of the possibilities offered by virtual machines. Second, we plan to deploy our honeypot at multiple diverse locations so as to derive more general conclusions about the observed attack processes.

"Benchmarking security protection mechanisms"
We aim to continue our work on the development of systematic approaches for the evaluation of security protection mechanisms, focusing in particular on intrusion detection systems. Our current evaluation framework based on Metasploit, which so far addresses network and operating system level vulnerabilities, will be extended to include vulnerabilities and attacks affecting web-based applications and services. The long-term objective is to set up standardized benchmarks for intrusion detection systems, and a flexible experimental evaluation framework that can be customized for different target systems.

Reactivity

Our research on dependable reactive systems will be developed according to two complementary approaches, related to online error detection and reconfiguration, and to software verification and testing.
With regards online reconfiguration, initial work will be devoted to the definition of online monitors to verify that a distributed real-time system complies with its specification. The second step is to devise an architecture able to use information provided by these monitors to reconfigure a failing component before the whole system fails.
Software verification and testing will be developed in two directions. The first one is in the lineage of previous work that seeks better integration of techniques used to verify software development artifacts. As model-centered approaches are now widespread in the development of industrial systems, we will investigate the coupling of model-checking and model-based testing. Our second research direction is more prospective, and will address a novel application of heuristic search techniques to probabilistic test generation.

Architecture

"Distributed online error detection" — We consider critical distributed control systems in close interaction with their operational environment. In this context, strong real-time or temporal specifications must be satisfied.
We will investigate the concept of *distributed real-time monitors* that verify at run-time that the system complies with its specification. Based on our previous work on this topic for centralized systems,

we plan to provide a framework that will signal an error (i.e., a deviation from the specification) as soon as possible, which is a crucial feature in systems with strict timing constraints. A necessary step in this direction is to be able to reason on specifications that combine timing constraints and distribution, possibly by extending timed automata, a classic tool for specifying real-time systems.

"Online reconfiguration" — A second challenge is to use advance information on an impending error in the system to reconfigure a suspected component before a global system failure occurs, by automatically selecting a degraded component with a weaker specification.
To attain this goal, it is necessary to refine the system architecture to include different variants of functional building blocks, together with support for handling changes in system configuration. Ideally, we will provide a framework for defining "cascaded" specifications, with different levels of service, that will be used by a run-time system to react to component failures before the whole system fails, thus increasing the system's availability.

"Preventing language-induced software faults" — Some fault types are specific to the modelling and programming languages that are used. We aim to identify such fault types, to assess their occurrence, and to propose guidelines to prevent their creation. However, the innovative features of languages leading to these fault types (e.g., inheritance mechanisms of object-oriented languages) are also potential means of prevention of other faults. We propose to identify and to evaluate these benefits, in order to deduce a pertinent overall assessment of actual fault risks integrating positive and negative effects of these features.

Analysis

"Testing and formal verification of behavioral models" — Work will continue on the definition of test languages well suited to model-based practice in the domain of critical embedded systems. In addition, we will start joint work with the OLC group toward the integrated use of model-checking and test selection methods. When the size of models, or even undecidability problems, prevents the applicability of model-checking, our proposal is to use model simulation as a pragmatic way to achieve partial verification. By "executing" a model with selected scenarios, it is possible to explore a (small) subset of all potential behaviors. The efficiency of this technique depends on the number and relevance of the scenarios supplied to the model, which can be seen as a test selection problem. We will investigate selection strategies that combine coverage methods coming from the software testing technology, and methods coming from the model-checking technology, like the exploitation of model symmetries.

"Search-based statistical testing" — The *statistical testing* approach, developed by our group in the nineties, involves the use of coverage criteria to design sampling profiles over the input domain. Search-based testing consists in using operational research techniques to generate test data. Recently, researchers at the University of York have suggested a novel application of search techniques: derive probability distributions for our statistical testing approach. The objective of the search is then no longer a data input, but a probability distribution from which the inputs are drawn. In collaboration with York, we will investigate means to put the idea into practice. This raises challenging issues, such as which encoding of distributions is the most effective for automated search, or how to incorporate expert knowledge into the search process. Also, the automated search framework will open new perspectives to consolidate the body of knowledge acquired from past experience, by allowing empirical studies of the behavior of statistical testing (e.g., to assess its robustness with respect to variations in the used distributions).

System Engineering and Integration – ISI –

Context and Challenges

The master of the development lifecycle of heterogeneous systems is a major stake. The heterogeneousness is to be taken into account inside a same system or in different systems interaction in the case of systems of systems. The growing complexity of systems in terms of the number of functions is increased by the necessary coexistence of different models and formalisms. The issues of coherence, interoperability, completeness of verification and validation, require new design methodologies. The general objective we are aiming at through this project is the master of the design of heterogeneous systems and the optimization and reduction of the design cycle.
We propose to structure our research in three main axes: design of heterogeneous systems, system integration and simulation, complex systems and systems of systems.

In this project we assume that two of our colleagues will soon join our research group. Indeed, Claude Baron, professor, and Guillaume Auriol, assistant professor, have started the process that will lead to their integration to ISI. This decision is motivated by the fact that we have been working together on different projects for many years. The research orientations of Mrs Baron and Mr Auriol are close to ours and we have decided to consolidate our research projects.

Major research orientations and projects

Design of heterogeneous systems

"Objective 1" — *The first objective is to propose a* heterogeneous systems design methodology that is based on MDE (Model Driven Engineering) and the EIA-632 standard recommendations. It also aims at introducing the validation of the requirements in the different phases of the design process.

"Problem statement" — The need to reduce the design cycle and control of the heterogeneity requires the formalization of requirements and their validation as soon as possible in the development cycle.

The formalization of the requirements, especially non-functional requirements, facilitates their integration into models. But there are still questions that are difficult to answer: How far is it possible, when and what is possible? The solution lies in the production of representative models that permit the formal analysis or the simulation. It is also necessary to establish links between the normative models (formal modeling of the system) and predictive ones (predict and validate its behavior). This difficulty is increased by the heterogeneity of systems that requires the use of different types of models.

"Approach" — The first research orientation deals with management of the functional and non-functional requirements for incremental validation. While the functional requirements can be prioritized through the formal models, the non-functional requirements often depend on the level of abstraction of the system. For example, a cost requirement may correspond at a given level to an architecture compromise while at another one it will result in an optimization analysis with no direct relation to the previous level. Therefore, incremental validation can limit at each level of abstraction the number of requirements. Validation can be done by simulation, and then regarded as an aid to design. Integrating the use of simulation in the early stages and during different phases of the design process is to guide the choice of decomposition, and hence reduce the design cycle. Introducing and using simulation models early in the design cycle can do this.
The formalization of the requirements will be based on the model transformation along the design process, starting from non-formal expression of requirements to models appropriate to the expected verification (formal models or simulation models). To ensure this passage, the IDM approach proposed should allow the transformation of activity and sequence diagrams of SysML to Petri nets, activity diagrams to define the dynamic behavior of the system and sequence diagrams scenarios test. This model transformation will formalize the transition from normative models to predictive models.

Another crucial point that complicates the task of formalization is that the systems are heterogeneous (several formalisms expression or several models).

It will therefore be necessary to introduce and propose a multi-models to be incorporated into an approach led by model driven engineering (MDE). It will identify models and tools to demonstrate the feasibility on application cases. To do this, it will be necessary to define and characterize the non-functional requirements, and also determine the possibility of their being taken into account at each level of development.

The demonstration of this methodology will be considered in further developing of Hiles tool. It will be inserted in the toolbox of the platform supporting the project TOPCASED, studying the possibility of introducing the concepts of co-simulation, and also by performing the transformation of models of activity and sequence diagrams to Petri nets.

"Objective 2" — Help to improve the system engineering process by proposing a new approach to minimize the design flaws that may affect the safe operation of the developed system.

"Problem statement" — The constraints imposed on the development cycle of a system are becoming stronger. The number of features of a system has increased dramatically and poses new dependability problems. These features are included in the new standards. To enable a cycle of development consistent with this growth and capable of meeting all the requirements of the early stages it is important to integrate the issues of dependability in the system engineering processes.

"Approach" — Studies and observations have shown many examples of systems containing errors of design, sometimes in large quantities and / or high severity, which were not addressed or even identified during the development cycle. These design faults are precisely originated in the development process.
The ESACS project has developed a methodology and a platform to help engineers automating certain phases of their work. But it did not consider the traceability of dependability requirements and analysis of human risk, among others. The ISAAC project, which is a continuation of the ESAC project, proposes to take into account the human error, this by injecting human errors in formal models. However, these two projects are mainly focused on formal methods of dependability but not really on a global approach.
The proposed methodology is an approach led by the models (MDA: Model-Driven Architecture), while respecting the process of EIA-632. It begins with the early stages of the development cycle or the elicitation of the requirements to the proposal of the logical solution, based on the use of modeling language SysML, itself based on UML 2. In fact, SysML and its panel of diagrams offer a real support for supporting a methodological guide in system design and development of the system architecture.

However, when approaching the physical solution, it appears that the semantics of SysML does not seem quite complete. That is why we want to integrate the language AADL to our approach, which seems best suited for our problem. In addition, there is a UML profile of AADL that can be added to SysML

System integration and Simulation

"Objective" — Optimization of the verification and validation by taking into account the simulation constraints at all levels of a system and by the encounter between the simulation and the use of the results of formal methods.

"Problem statement" — The analysis of heterogeneous systems is difficult because of the coexistence of several description formalisms or different levels. Research results of formal verification of a given formalism are well known today. But in the presence of two or more different formalisms, it is only the simulation to analyze the complete system
To manage the complexity of analysis introduced by the coexistence of several different formalisms or levels we will use the concept of component-based systems because it contributes to the interconnection of heterogeneous models (interdisciplinarity and interoperability), reuse and virtual prototyping. This process of simulation and in particular co-simulation will enhance the process of partitioning with the inclusion of joint constraints of "meet in the middle" (reuse, technology, levels of abstraction...)

"Approach" — Several studies show the need to build complex or heterogeneous systems in composition to get the maximum benefit of all formal results that can be expected from a model or a given formalism.
This method allows propagating certain properties by construction. It is recognized that the composition enables encapsulation of information, a natural heterogeneity and availability at a given level of abstraction of relevant information.

The composition is therefore seen as a process of integration for which the simulation will allow a consistent analysis. As suggested in the issue description we break the simulation into three parts:

• The creation of an enabling environment to implement the demands of the real system.

• The formalization of the simulation in order to generalize and take into account all the elements proposed by each formalism (observation) and that can contribute to the improved results of the simulation.

• The generation of stimuli that aims to address what the present formalisms cannot afford to deal with formally. The objective is to reduce the testing and trying to assess what the tests do not cover. Moreover, this generation may be a way to validate strategies for V & V.

We plan to build on the theory of integration and simulation of complex systems of B. Zeigler and extend to systems based on Petri nets.

In general, we reposition in this context all the problems related to interoperability and the co-simulation with the consideration of physical components and co-design.

"Frame" — We want to apply this approach of integration in the context of strategies for V & V in

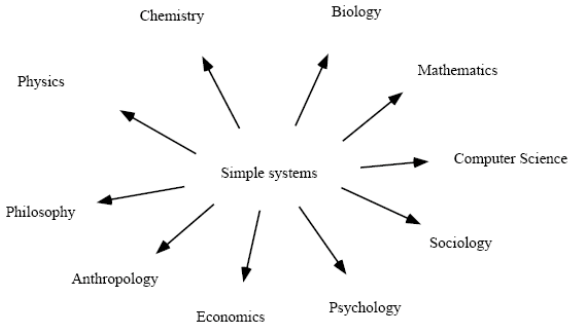
the process of EIA-632 (System Engineering)

"Platform" — We want to use all available simulation tools and the results of different formal methods. For this, the demonstration platform will be based on co-simulation (distributed or not distributed) and as potential candidates (Hiles, Topcased ...)

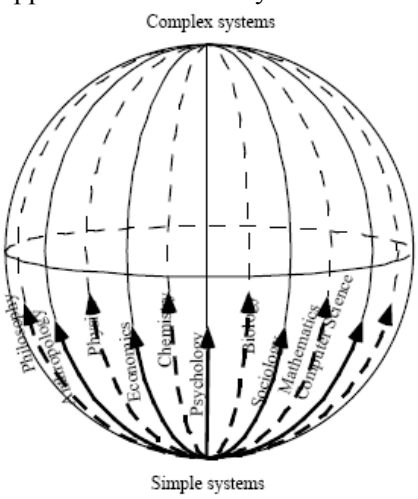
Complex Systems and System of Systems

"Objective" — The objective is to see the new systems understanding either physical systems or biological system as interacting systems with their own rules that may have some common basis of understanding. Systems engineering tried and succeeded to have a common basis in systems development. The short term objective is willing to study emergent properties in systems development; however the main stream of actual research is to further understand the social and biologic and physical systems and hence the eventuality to set up an institute in this context.

"Introduction and state of the art" — Complex systems is becoming an explicit new field research as more institutes are created to address the research issues (NECSI at Massachusetts, MS&E at Stanford, IXXI at Lyon, Paris, French national network of complex systems ; European complex systems…). It encompasses the disciplines as to have a unifying view for systems models and from simple entities that are best represented from a classical view that make emergences of disciplines as



to a new approach illustrated by



"Problem statement" — Working with complex systems induces a variety of approaches due to their intrinsic inter-disciplinarity. Since a scientific discipline can be roughly defined via four major axes: its objects of study, its questions, its methods and the kind of developed results, inter-disciplinarity can appear for different reasons, depending on which of these axes different disciplines are involved. In the case of complex systems, the central question is to study the global behavior of a set of entities interacting via local rules. Inter-disciplinarity appears on the objects side, since they can belong to any discipline biology, physics, economy, social sciences, and on the methods side, since methods can come from any of these fields, very often they come from many of them.

The main problems researchers in complex systems want to address are the understanding, in general or for a particular object involved in a complex dynamical process, of the notions of emergence, self-organization, adaptativeness, but also of robustness to perturbations and intrinsic unpredictability.

"Approach" — *Approaches on specific topics and expected results:*

When working in systems engineering, there was a will to unify processes to design systems whether systems are mechanical, software systems or electrical. Such paradigm of view is just being the same when addressing complex systems.

We see many approaches and directions of research, one promising direction is to use context approach by identifying and modeling interfaces. We come to the basics and the famous inequalities

System ≠ S components

global Optimum ≠ S Local optima

Modeling issue is common to all disciplines and depending on facilities available we can go to the simulation phase when needed suing other lab facilities. The perspective is also to organize events on the matter locally and inviting all national and international institute working on complex system. A possible perspective is the creation of an institute of complex systems at south west region of France.

Distributed Computing and Asynchronism – CDA –

Context and Challenges

Context

The evolution of Computer Science during the recent years has changed our vision of computing, programming and using machines. The size and complexity of applications and problems to treat have led to a race for high performance that has imposed the concept of parallelism in computer architectures. This phenomenon can be seen almost everywhere, i.e. from supercomputers to desktop and laptops. Now, the architectures of processors are based on the use of many cores and specialized units like GPU are even used for general purpose parallel computing. Simultaneously, networks technologies have known an important rise, parallel and distributed computing have converged and concepts such as clusters or peer to peer networks have emerged.

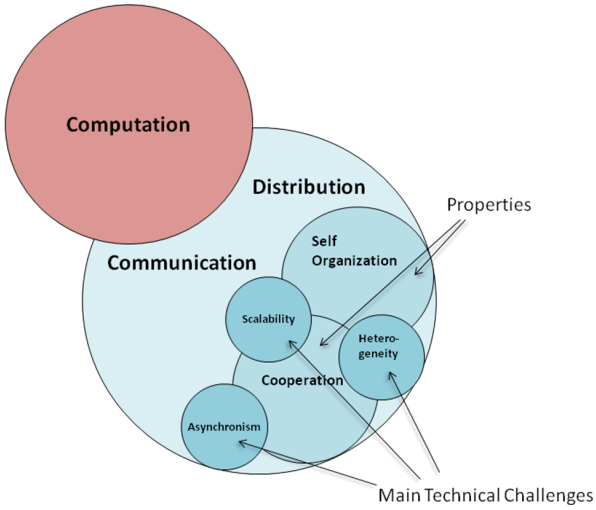


Figure 1: Main technical challenges in distributed computing

Challenges in distributed computing

The lack of centre and global clock together with a priori unbounded communication delays (i.e. asynchronous model), massive parallelism and heterogeneity lead to interesting problems. We note that technical challenges in distributed computing are not limited to the problems quoted above (one could quote also cooperation in presence of faults and topology changes i.e. node volatility and link failure and many more technical challenges). Nevertheless, the challenges quoted above seem to us key technical challenges and we plan to address them. More generally, these technical challenges can be identified as part of broader "Grand Challenges" like:

a) Easiness of programming and using massively parallel or distributed architectures

b) Quest of efficient parallel or distributed methods.

Some computer scientists like Rodney Brooks and Michel Raynal consider that those "Grand Challenges" are among the most important ones in Computer Science and that the future of this science depends greatly on our capacity to address these important questions.

Strength and opportunities

The circumstances quoted in the first subsection are very propitious to studies led by scientific researchers of our team who have worked for a long time on parallel and distributed computing. Researchers in our team are affiliated to two important scientific schools in France: first, a school dealing with scientific computing led by Jean-Claude Miellou; secondly, a school in Combinatorial Optimization and Computer Science led by Gérard Plateau. As previously said, the situation of our team is quite unique if one thinks at our research works which are conducted at the intersection of Computer Science, Applied Mathematics, Control Theory and Numerical Analysis. This excellent situation has permitted us to establish fruitful collaborations with researchers in this country and abroad. Multi disciplinal approach is also an advantage in order to produce new scientific results in this domain. As a consequence, we believe that the future of the DCA team which was founded ex nihilo in October 2007 according to the advices of the previous Evaluation Committee of LAAS-CNRS will be very good.

It is worth noting that there is no team in LAAS-CNRS doing research work specifically on the topic of parallel and distributed computing and that there are relatively few teams in this country that are developing research works in this domain. One can quote essentially Computer Science teams dealing for example with principles of distributed computing, models of distributed algorithms or global computing environments; none of these teams is specifically positioned on asynchronism and self organization.

Parallel and distributed computing is widely studied in the world. Nevertheless, except for few teams in Universities like MIT and Temple University, Philadelphia, that have produced scientific results at the intersection of Computer Science and Applied Mathematics, the bulk of research works is in Computer Science, i.e. programming models, programming environments, fault tolerance and security or performance study.

Major research orientations and projects

Research Orientations

Research orientations of DCA concern easiness of using and programming parallel and distributed computing systems at a very large scale and design of efficient parallel and distributed algorithms. DCA will work on decentralized environments for high performance peer to peer distributed computing and high performance distributed computing on general purpose architectures and dedicated architectures. In particular, DCA will deal with the solution of large scale numerical simulation problems like boundary value problem. DCA will also deal with NP complete integer programming problems like multi knapsack problems and knapsack sharing problems. There are real challenges in order to find out exact solutions of more difficult problems or problems of larger size.
The two topics that we aim particularly at studying are: asynchronism and self organization.

"Thorough study" — DCA will deal with the concept of asynchronism, a key concept in order to understand and address the very nature of distributed computing and efficiency issues. As a matter of fact, asynchronous algorithms are well suited to all type of networks and one cannot reasonably think at synchronizing processes or processors in a massively distributed or parallel system. On what concerns specifically high performance computing, it turns out that the use of asynchronous algorithms permits one to obtain better efficiency when parallel tasks are unbalanced or when convergence is monotone. Asynchronous schemes of computation permit also one to obtain some fault tolerance since one can show that asynchronous algorithms converge even when some data are lost (see [BT89]).

It is important to note that asynchronism is about to become one of the main topics in Computer Science. This topic encompass the numerous facets of the same concept which consists in letting entities go at their own pace; it can be found in various areas of research; e.g. one finds this concept in circuits, communications, processes and algorithms. Let us conclude on this topic by saying that asynchronous schemes of computation are becoming more and more popular nowadays and that research works on communication libraries like Open MPI are pursued at University of Tennessee and other universities, in order to facilitate the use of asynchronous algorithms for high performance computing purpose. Users of massively parallel architectures like Christian Engelmann at Oak Ridge National Laboratory recommend also the use of asynchronous algorithms.
We shall work in particular on convergence study and stopping criteria of parallel or distributed asynchronous iterative algorithms applied to linear or nonlinear fixed point problems. This last topic is a very difficult issue that is nevertheless central if one wants to master implementation of asynchronous algorithms and facilitate their use. We shall use the concept of sliding macro iteration which is an interesting tool in order to derive accurate stopping criteria (see [ACL502]). We shall concentrate on the effect of round of errors in boundary value problems. Implementation issues will be studied in particular, in the framework of ANR project CIP presented in subsection 2 of this Section.

"Breakthrough" — DCA will also deal with self organization. Self organization appears to be another general key concept in distributed computing despite the fact that, to the best of our knowledge, it has received a limited amount of attention in this context so far.

Far beyond self optimization or overlay network topology maintenance, self organization is an important property in distributed decision making that permits one to obtain efficient behavior particularly in hazardous situations or in the presence of faults and insure everlastingness of applications.

For example, one can find for this important property in human or animal societies like swarms where several strategies are developed in order to insure a certain level of efficiency of the group (it turns out also that systems that cannot adapt themselves to evolution are finally condemned to dysfunction and extinction).

This topic will be treated in particular in the framework of ANR project CIP that deals with peer to peer distributed computing (see subsection 2 of this Section). Frequent storage of data at neighbors (i.e. other peers), peers watching and computational task reallocation can constitute an interesting first practical approach in order to deal with robustness issues. Characterization and modeling of self organization phenomena will also be studied. Strategies using techniques issued from Artificial Intelligence will be considered.

Projects

Considering a short term horizon, we recall that DCA is the global coordinator of project ANR CIP that deals with high performance peer to peer distributed computing (see [EXT2]).

CIP was funded by ANR in 2007 in the framework of the so-called “Calcul Intensif et Simulation”, CIS, call for proposals. The partners of the project are: LAAS-CNRS, IRIT-ENSEEIHT, University of Picardie, University of Franche-Comté and Euromedtextile.

The goal of this project is to develop a decentralized environment for high performance peer to peer distributed computing that allows efficient direct communication between peers (see Figure 2). This is an example on how we plan to address the easiness of use "Grand Challenge" and heterogeneity and scalability technical challenges.

The environment is based on a self adaptive communication protocol whereby choice of communication depends on both application level decisions, like choice of computation scheme (e.g. synchronous versus asynchronous iterative schemes) and network level elements of context like topology (e.g. adherence to a given cluster or nearness of peers). The self adaptive protocol based on a modified Cactus framework makes wide use of micro protocols (see Figure 3).

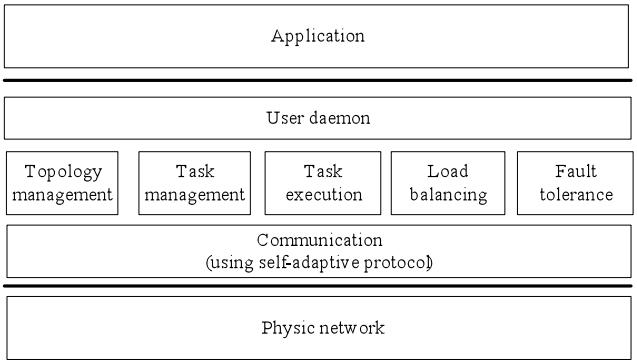


Figure 2: Decentralized environment architecture

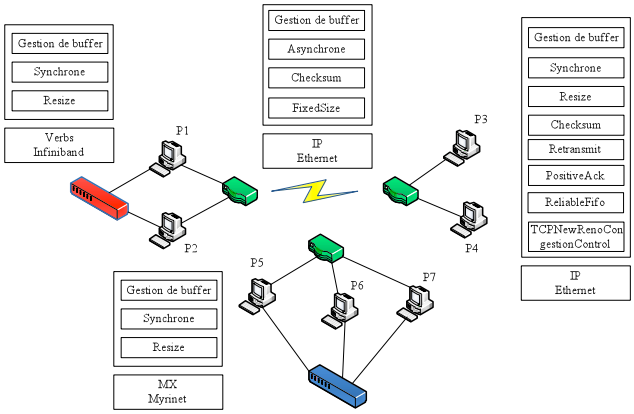


Figure 3: Example of micro protocols scenario

Market solutions are rather grid or global computing solutions (i.e. solutions that are not totally decentralized or whereby all nodes do not see the network the same way) than true peer to peer solutions. Peer to peer networks seem to be an economic and ¨green¨ solution for large scale distributed computing in industrial or academic sites. As a consequence, there is a real economic and ecologic stake at developing decentralized environments for peer to peer distributed computing applications.

Aside from the development of a self adaptive protocol and environment for peer to peer distributed computing, the project deals also with simulation of large scale peer to peer distributed computing and performance prediction (University of Franche-Comté). Finally, project CIP develops also a series of distributed solvers in financial mathematics, process engineering (IRIT-ENSEEIHT) and logistics (University of Picardie). Experiments will be carried out on the Laasnetexp network, NICTA network and Grid 5000.

We plan also to study task deployment and scheduling on large scale peer to peer distributed computing networks. This last work related both to Computer Science and Applied Mathematics (Integer Programming) will permit one to enhance efficiency of the network.

The DCA team will study distributed computing on dedicated architectures. This work will be the continuation of ANR project Smart surface (see [EXT3]). Clearly, distributed computing (e.g. distributed state acquisition and concurrent pattern recognition) on a dedicated architectures like a smart surface is the source of a rich problematic mainly due to the scarcity of resources like number of sensors, memory size, computing power and also to the presence of faults. This kind of architecture can illustrate also the benefits of asynchronism in distributed computation. We note that those research works are closely related to classical works made in distributed computing (e.g. obtaining the global state of a given distributed system for termination detection purpose or other purpose).

DCA will also work on efficient parallel or distributed algorithms for difficult integer programming problems. In this last case, research works will be undertaken in the framework of working group Knapsack and Optimization, KSO (cofounded by DCA) of GDR RO (see [EXT4]). DCA will concentrate on multi knapsack problems, knapsack sharing problems and real time logistics massification problems combining truck loading and vehicle routing. These complex problems are central to logistic companies that must take decision in quick time and have to face truck and loading systems faults. There is a real technical challenge in solving problems that are more complex or bigger. Parallel cooperative methods combining dynamic programming and branch and bound or branch and cut will be proposed.

New architectures like Graphic Processing Unit, GPU, will be also investigated. GPU like NVIDIA boards that have many cores are very interesting with this respect since they are widely available, economic and highly parallel; they take also benefit of available

tools like CUDA. Some solutions like GPU computing or CPU/GPU computing, i.e. solutions that combine the power of CPU and GPU (since computations can be done in parallel on the two boards) are currently under investigations by our team. Preliminary results show some speedup for integer programming problems. We shall concentrate in particular on the benefit of using many cores for irregular applications.

Organization of Scientific Events

DCA will organize several scientific events in relationship with distributed computing.

Dr. Didier El Baz and Moussa Elkihel will organize and chair the invited session: ¨Méthodes Parallèles ou Distribuées pour la Programmation Entière¨ that will be held in conjunction with the conference ROADEF 2010, Toulouse (see [EXT5]).

Dr Didier El Baz will organize and chair the 4th international workshop on Modeling, Simulation and Optimization of Peer to peer Environments, MSOP2P 2010, Pisa Italy, that will be held in conjunction with the international conference PDP 2010 (see [EXT6]).

Summary

Our research work will concern easiness of use and programming of massively parallel or distributed architectures as well as efficient distributed or parallel algorithms. It will span from the design and analysis of parallel or distributed algorithms to communication study, load balancing techniques analysis and design of distributed computing environments. We shall deal in particular with high performance distributed or parallel computing on general purpose or dedicated architectures with emphasize on asynchronism and self organization. We shall concentrate on large scale or difficult problems like nonlinear boundary value problems and integer programming problems. Our studies will be multi disciplinal, being related both to Computer Science and Applied Mathematics.

More generally, the problems we shall consider open on a wide class of complex problems dealing with understanding and managing or optimizing (e.g. for production purpose) large scale systems made of cooperating or interacting entities, i.e. companies, robots, or humans that are not limited to data exchanges but that can also exchange items or goods.

References

[BT89] D. Bertsekas, J. Tsitsiklis, Parallel and Distributed Computation, Numerical Methods, Prentice Hall, Englewood Cliffs, 1989.

[ACL502] J.-C. Miellou, P. Spiteri, D. El Baz, A new stopping criterion for linear perturbed asynchronous iterations, Journal of Computational and Applied Mathematics, Vol. 219, Issue 2, October 1, 2008, p. 471-483.

[EXT2] ANR Project CIP, ANR-07-CIS7-011: http://www.laas.fr/CIS-CIP/

[EXT3] ANR Project Smart Surface: http://www.laas.fr/SMART-SURFACE/

[EXT4] Working group KSO of GdR RO: http://www.laas.fr/KSO/

[EXT5] Invited session ¨Méthodes Parallèles ou Distribuées pour la Programmation Entière¨: http://roadef2010.fr/

[EXT6] MSOP2P 2010, Pisa: http://www.laas.fr/InternationalWorkshopMSOP2P/