LAAS

CNRS

Laboratoire d'Analyse et d'Architecture des Systèmes du CNRS

Activity Report 2005-2009

July

2009

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

LABORATOIRE D'ANALYSE

ET D'ARCHITECTURE DES SYSTÈMES

UPR 8001

ACTIVITY REPORT 2005 - 2009

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This document includes the general presentation and activity report of LAAS from January 1st 2005 to June 30 2009, detailed at the research groups level.

The list of publications is in a separate document.

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I. PRESENTATION OF LAAS

1. Introduction

The Laboratory of Analysis and Architecture of Systems (LAAS) is a CNRS research unit associated with four of the six founding members of the University of Toulouse: Université Paul Sabatier (UPS), Institut National des Sciences Appliquées de Toulouse (INSA), Institut National Polytechnique de Toulouse (INP) and Institut Supérieur de l'Aéronautique et de l'Espace (ISAE).

LAAS' research activities fall within the domain of Information Sciences and Technologies and address complex systems (artificial and sometimes natural) generally heterogeneous, and at different scales, to devise theories, methodologies and tools for modeling, designing and controlling them.

Research, innovation and transfer are tied. The lab has a history of strong relationships with industry and works in a large number of collaborative projects with international, national and regional industries of all size. LAAS was one of the 20 first "Carnot Institutes" labeled in 2006.

2. Scientific Research

The systems considered in our research are of different kinds: integrated systems, embedded systems with real time and safety requirements, distributed systems, mobile systems, autonomous and robotics systems, integrated systems, micro and nano systems, biological systems. They fall in various application domains such as aeronautics and space, telecommunications, transports, production, services, security and defense, energy management, healthcare, environment and sustainable development.

The scientific topics are distributed in four main research areas or domains:

- **Micro and Nanosystems** (MINAS): MEMS/NEMS and MOEMS, RF and microwave systems, systems and devices for energy management, nanophotonics and photonic integration, Bio MEMS and nanobiosystems, modeling and simulation of micro and nanosystems.
- **Systems Modeling, Optimization and Control** (MOCOSY): Non-linear systems, robust and adaptive control, filtering and signal processing, network management and quality of service, diagnostic and supervision, optimization, scheduling and production planning.
- **Critical Computer Systems** (SINC): Dependability, computer systems safety and security, critical communication systems validation and verification, systems engineering, and distributed computing.
- **Robotics and Artificial Intelligence** (RIA): Environment perception and modeling, motion and action planning and molecular motion, cognitive robotics, human-robot interaction, humanoid robotics, manipulation, field and aerial robotics, multi-robot systems.

In addition, in our laboratory project (see the "Project" document), two transversal axes were defined across domains and groups: interactions with the living at different scales, and ambient intelligence.

In this document, the foundational issues and the results in all these topics will be developed in each individual group report.

3. Organization and Scientific Policy

The basic scientific organizational unit at LAAS is the "**Research group**" which is defined by a set of scientific subjects and objectives and composed by researchers pursuing them (CNRS and university professors, post-docs and PhDs). A group has its own resources and external projects (and contributes to the common lab budget), a director and a scientific committee that meets every month. The size of a group is variable, and its lifetime is 4 years, renewable according to evaluation. In order to address new directions that may stem from existing groups, to launch new activities that differentiate from ongoing ones, or to encourage researchers with novel perspectives, an entity called "**Operation**" can be created for a period of 2 years, which may become a full group after evaluation.

Currently there are 17 research groups and two operations. A group's scientific objectives fall in one of the **four domains** mentioned above, even if there are collaborations between different groups across different domains. Actually this is encouraged through "**LAAS Projects**", a periodic call for proposals on open subjects, financed internally after evaluation and selection by a project committee. Within each Domain, there are coordination and consultation structures for sharing research orientations, equipments and defining priorities.

Technical support is provided by a number of engineers, technicians. This personnel is organized in two common technical services (**II or 2I**: Informatics and Instrumentation, and **TEAM**: Techniques And Equipment for Microelectronics). Administrative clerks are organized into 7 common administrative and support services (figure 1).

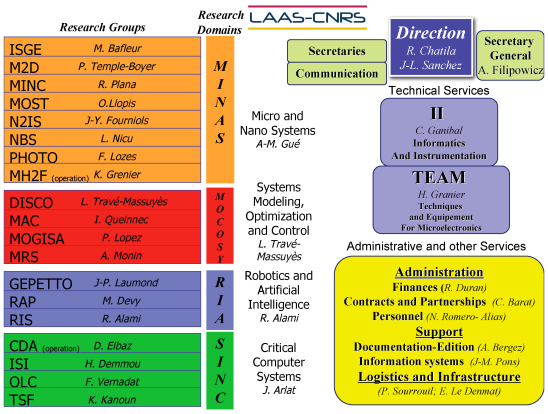

Figure 1. LAAS general organization

Requests for technical personnel by the groups are examined by two *ad hoc* committees (COMTEAM and COM2I) under the authority of the lab's director. Requests for equipment of common, or of specific, interest are also examined by an *ad hoc* committee (COMEQ).

4. Personnel

One of the largest labs in France, LAAS has a personnel in 2009 of the order of 635 persons, among whom 200 researchers and university professors, 115 Engineers, technicians and administrative clerks, 45 post-docs and visiting scientists, and 275 PhD students. Besides, LAAS hosts every year about 200 Master student interns from different universities and engineering schools, and is strongly involved in education and training.

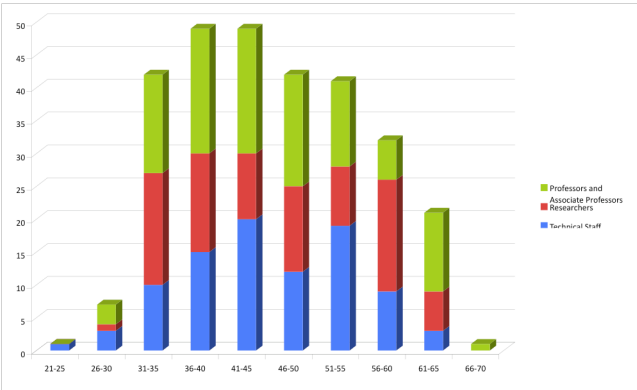

Table 1. Age distribution of permanent personnel

The age distribution shows a rather correct renewal of the research (Professors and researchers) personnel – although this is not necessarily evenly distributed among the research topics. But there is a concern on the renewal of technical staff.

5. Scientific Production

In terms of scientific production, LAAS has pursued a policy of dissemination and has encouraged teams and individual to publish in priority in international journals. The next table compares the scientific production of the elapsed period with the previous four years period (2001-2004). There is stability in terms of books and chapters but international journals were increased by a factor of more that 1.5 and international conferences by 1.9, not counting the invited papers. Stability in HdRs has triggered a policy for defending them and the year 2010 will see an increase. On the other hand the number of defended PhD theses has increased by a factor of 1.3 which shows the vitality of LAAS in proposing innovative scientific topics.

Scientific production	2001-2004	2005-06/2009
Books and Chapters (DO, OS)	95	100
Scientific Journals (ACL)	399	617
International Conferences (ACTI)	811	1549
National Conferences (ACTN)	649	351
PhD Theses	165	222
Habilitations	15	17

Table 2. Comparison of scientific production over the past two 4-years periods

6. Budget

The following tables show LAAS global budget and operational budget over the reporting period. There are some clear tendencies such as the importance that public agencies – namely the ANR – play today in financing research projects. CNRS endowment is rather constant over the years, and the Educational institutions endowment, which has always been small, tends to be reduced.

	2005	2006	2007	2008
Endowment: CNRS	2 680	2 603	2 542	2 547
Endowment: Education Institutions	266	246	165	158
Salaries (Staff)	13 124	14 279	16 093	17 012
Salaries(grants for docs)	2 470	3 108	3 471	2 648
Research contracts	5 669	8 694	13 157	13 646
Total	**24 209**	**28 930**	**35 428**	**36 011**

Table 3. Global budget (incl. salaries) over the past period

The importance that national research contracts takes in the budget mainly due to the creation of ANR, but also to projects financed by the ministry of Industry in the framework of the support to competitiveness clusters show how much LAAS is dynamic in

answering to the calls for proposals and in building collaborative projects with industry.

Industrial contracts tend to grow. This growth could be more important and encouraged by the governmental regulations on taxes, which should lead industry to sign more direct contracts with academia.

LAAS involvement in European projects has always been important. However there is clearly a competition now between answering to ANR calls or to EU calls given the saturation of researchers. In terms of financial return, the cost model negotiated by CNRS during FP6 was certainly not the best.

	2005	2006	2007	2008
Endowment: CNRS	2 680	2 603	2 542	2 547
Endowment: Education Institutions	266	246	165	158
contracts	867	555	2 873	663
Europe	938	2 124	1 880	1 417
Public Agencies (ANR, MINEFI, ...)	2 718	5 281	6 894	9 781
Industry	1 146	734	1 510	1 785
Total	**8 615**	**11 543**	**15 864**	**16 351**

Table 4. Operational budget evolution over the past period in KEuros

	2005	2006	2007	2008
Endowment: CNRS	31	23	16	15
Endowment: Education Institutions	3	2	1	1
Regional contracts	10	5	18	4
Europe	11	18	12	9
Public Agencies (ANR, MINEFI, ...)	32	46	43	60
Industry	13	6	10	11
Total	**100**	**100**	**100**	**100**

Table 5. Operational budget evolution over the past period in percentage

Salary expenses tend to grow. This is a direct consequence of the project-oriented financing which requires to hire PhDs, Post-Docs or engineers to work on the projects. As a consequence, travel costs also grow (mainly participation in conferences and project meetings). The high figure on equipment is in large part due to the BTR plan.

	2005	2006	2007	2008
Salaries (from resources)	2 329	2 365	3 390	5 201
Operating costs	1 854	1 867	2 337	2 627
Equipment	4 656	3 335	2 864	4 517
Infrastructure	987	839	1 431	1 189
Travel	1 347	1 499	1 868	1 926
Total	**11 173**	**9 905**	**11 890**	**15 460**

Table 6. Expenses from operational budget over the past period

7. Technical Facilities

LAAS research activity requires important experimental and technological development facilities. These facilities are common technological resources organized in different platforms shared among the groups and open to outside users form academia or industry.
During the period 2005-2008 the infrastructure and the equipment of these platforms were significantly improved.

The Micro and nanotechnology platform
One of the 7 Technology Platforms of the National "Basic Technological Research" network. Since April 2007 thanks the financial support of the Regional Council of Midi-Pyrénées, CNRS, ANR (RTB network) and a contractual financing from LAAS-CNRS and the "Affiliate Club" (see the relationships with industry section), the micro and nanosystems research activities benefits of 1500m² of clean room facilities consisting in:

- 180 m^2 labeled class 100 (photolithography room; electron beam lithography, under wet benches zone and alternative technologies zone);
- 900 m^2 labeled class 10000: (characterization, laser lithography, electroplating, chemistry, thin film deposition, plasma etching, MBE, ion implantation equipment, furnaces, assembly);
- 420 m^2 labeled class 100 000 (facilities and backend machines.)

The number of staff members involved in the activities amounts to 130 researchers, PhDs and post-docs, 26 engineers and technicians.

Figure 2. The LAAS Clean Room

The activities of the technological platform are supported by the TEAM technical service of 26 persons (14 engineers and 12 technicians). Each technical zone is managed by an engineer, with the assistance of a technician. Their main mission consists in supporting the LAAS research groups for their technological projects (already 70 in 2008). In addition since 2003, thanks the Basic Technological Research Network (BTR program), LAAS technological facility is a National platform opened to the academic laboratories as well as industrial and SMIs. Already 60 actions were supported in 2008.

The choice of the investments is based on the scientific needs and priorities of the concerned research groups and depends also on the strategy of the BTR network.

Four kinds of flexible and complementary equipment are targeted:

- non-automatic machines, used to process samples of several sizes and non-standard substrates,
- automatic and/or production machines, adapted to standard wafers (and facilitating technological transfer from research to industry),
- machines dedicated to specific processes, such as MOS technology,
- machines dedicated to non-specific processes to fulfill various demands (non standard substrates, new materials…)

Silicon technology processes concern mostly 4-inches and 6-inches wafers. However, some devices are compatible with 8-inches or 12-inches substrates. Besides, standard III-V GaAS substrates are 3-inches. Finally the implementation of the BTR plan coincides with developments on new materials, the now covered spectrum includes materials such as GaN, diamond, polymers, carbon nano tubes, etc.

Moreover one significant part of the equipment relates to emergent technologies such as Ink Jet, UV nano-imprint, micro contact printing and screen printing. These techniques are characterized by their "low cost" of implementation and the new developments they propose (deposits of new materials, replication on great surfaces of nanometric structures, *etc*.).

The Characterization platform

The LAAS Characterization Platform pools and organizes all the micro and nanosystems characterization facilities available at LAAS in the following domains: electric, microwave, optics and micro/nano systems for chemistry and biology. 4 engineers and technicians of the 2I service ensure the management of this platform.

Specific electrical benches and probe stations are used for the electrical characterization of semiconductor devices, micro and nanosystems and ESD tests and measurements.

In the microwave domain test benches and probe stations allow to characterize the S parameters and also to measure the phase noise and the low and high frequency noise. Several setups have been developed for RF MEMS reliability using in particular one cryogenic probe station. One anechoic chamber is available for the study of antenna.

In the optics/photonics domain equipments cover from material optical characterization to passive and active devices characterization (VCSELS, PhC lasers, detectors,…).

Specific test benches are available to characterize micro and nanosystems for chemistry in liquid and gas environment. We have also developed from scratch mechanical and electrical bio sensing characterization benches dedicated to micro and nanosystems for biology.

The Design platform

The design platform is based on 17 workstations and generic and specific simulation tools allowing to analyze and understand the electrical and physical behavior (mechanical, chemical, electromagnetic, and thermal) of semiconductor devices and micro/nano systems in view of their design. An engineer of the 2I service ensures the management of this platform (users training, help to the developments, storage of the works, administration of the material and software systems).

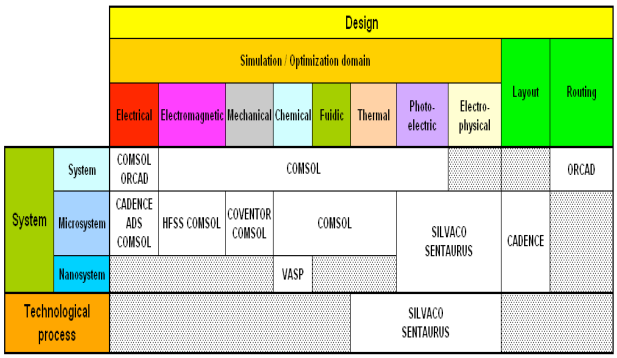

Figure 3. Software tools used in the Design Platform

The Robotics platform

The Robotics platform is composed of a pool of 9 autonomous robots (Three indoors robots: one humanoid and two wheeled robots, two field robots, and four unmanned aerial vehicles), in addition to a Cartesian robot and a motion capture room. Five staff members of the 2I service (3 electronics engineers, one computer science engineer and one mechanics engineer) are involved in this platform. Its objectives are to maintain and prepare the evolutions of hardware and software architectures of the robots fleet as well as teaching and providing help to its users.

Figure 4. Robots of the Robotics Platform (Rackham, HRP2, Jido, Dala, Mana and Manta)

Network platform

"Laasnetexp" is a multi-technologies, multi-services experimentation Internet platform for researchers in networking. This platform aims at experimenting and validating architectures, protocols and network mechanisms issued from our research, essentially on problems related to QoS in large scale heterogeneous networks, security, and communication in dynamic networks.

Experiments are performed in a multi-technologies, multi-domains and supervised actual environment, as well as in an emulation environment. This plateform will evolve in the future in the context of the ADREAM project (see the "Project" document).

The "Laasnetexp" network platform takes the form of a network domain, independent from the LAAS operational network, and directly connected to RENATER and GEANT, the European network for research.

8. Relationships with industry

LAAS has a large number of collaborative and direct projects with or involving industrial partners, at the national, regional, European or international level, and several dozens of such projects are launched each year. However, a privileged form of cooperation with industry is the "Joint Laboratory" which enables to define a long-term program (usually 4 years) of interest to the lab and the industrial partner that will be executed in common by engineers, scientist and PhD students. Four such laboratories exist over the reporting period:

- LISPA with Freescale on electrical power management for automobile
- AUTODIAG with ActiaGroup on fault detection and diagnostics.
- PEARL with ALSTOM on power management in trains.
- PIX-CELL with Essilor on the digital glass.

In addition, AIRSYS, a convention with Airbus on avionics and flight control plays a similar role.

LAAS is involved in the three competitiveness clusters in the Midi-Pyrénées region: Aerospace Valley, Cancer-Bio-Santé, Agrimip Innovation. In particular, members of the lab participate in the governance structures of the first two of them. The lab is also member of the Advanced Research Thematic Network "Sciences and technologies for Aeronautics and Space » (RTRA-STAE) which funds basic research to benefit to this application domain.

LAAS has set up an "Affiliate Club" which comprises currently 64 industries of all size. This structure is a means scientific and technological exchanges, a permanently open pipeline between the industrial pull and the academic push. It organizes frequent meetings on selected topics of interest where industry and research meet and define future projects.

The lab encourages and provides assistance to researchers who want to start up their companies to disseminate research. In the past few years, five start-ups were created (Kineo, QoS design, NeoSens, Tag Technologies, Noomeo), the last one during the reporting period.

9. International Cooperation

LAAS was involved in 38 European projects and actions during the reported period, 16 STREPS, 6 IP, 5 networks of excellence, 6 coordination actions, 3 EUREKA and MEDEA, 1 European Defense Agency contract, and 1 European associated laboratory. Among these projects LAAS is/was coordinator of one IP, 2 STREPS, 2 coordination actions, 2 networks of excellence and 1 European associated laboratory.

Scientific partnership with international laboratories is an important objective for LAAS research groups. A strong collaboration exists with US (University of Urbana Champaign, Dallas University, University of Southern California), and ties exist with MIT and Stanford University. Cooperation with South America (Mexico, Brazil, Venezuela,..) and Japan is very important. The Last four years LAAS has continued its relations with Japan through the LIMMS (Laboratory for Integrated Micro-Mechatronics System), and the JRL. Three researchers and one engineer spent two years in LIMMS and one of them was director of this lab.

With the perspective to increase international relationships with new countries we have launched specific actions with Taiwan, which led to partnerships with the National Technical University and the National Academia of Taipei but also with the NCKU in Tainan. These partnerships allowed to develop joint projects with exchanges of PhDs and post-docs. Furthermore LAAS continues to enhance its international relations with US and South America who led to new partnership with Georgia Tech and with the CINVESTAV (Mexico).

A specific mention should be made of the French-Japanese JRL Laboratory (2005 - 2008). Created on 2003 by the CNRS and the National Institute of Industrial Science and Technology (AIST, Japan), the International Associated Laboratory (AIL) Joint Japanese-French Robotics Laboratory (JRL) is specialized in robotics research, particularly in humanoid robotics. Since November 2005, the JRL is organized on two sites: JRL-Japan located at AIST Tsukuba and JRL-France at LAAS. Researchers of two nationalities are involved in both sites. On the

French side, JRL is composed of the core researchers from LAAS and LIRMM (Montpellier). Led by those researchers, the JRL collaborates with other French research teams.

Various projects at LAAS benefit from the humanoid HRP-2 robot platform (1.54m, 58kg), as well as from software and human resources. This platform is open at the national level to welcome projects of teams from outside LAAS: during the considered period, HRP2 has been the support of a total of 15 projects involving 10 different teams.

Since the creation of the JRL, about a hundred articles have involved French and Japanese researchers have been published. The progress made on the platform at LAAS is mainly on the advanced motion control and the biped locomotion. Today the HRP-2 robot can for example find a ball on the basis of its color, localize it, approach to the place where it is located while avoiding obstacles, grasp it and place it on the designated position.

It is thanks to the work achieved in this framework that the CNRS and AIST created the International Mixed Unit (UMI) CNRS-AIST JRL (Joint Robotics Laboratory), UMI3218/CRT located at Tsukuba, while the CNRS keeps the potential to support research on the platform at LAAS.

10. Education and Training

LAAS is involved in master degree research and hosts the two doctoral schools GEET (Electronics, Electrical engineering and Telecommunication) and EDSYS (Systems) linked to the main scientific research domains of the lab. LAAS personnel is significantly involved in LMD degrees of the University Paul Sabatier and also in the engineering schools of Toulouse, INSA, ENSEEIHT, ISAE, ENAC. Many permanents members of LAAS assume responsibilities in these different institutions (see annex 1). Among the most important ones that can be mentioned are: the direction of the Computer Science and Electrical Engineering Departments of INSA, IUT and of the Electrical Engineering Department of University Paul Sabatier, the direction of the doctoral school GEET, the direction of the scientific council of the Unit of Research and Formation (UFR) of Physics, Chemistry and Automatics of the University Paul Sabatier, the direction of the CIES (initiation to the higher education), Vice presidency of the University Paul Sabatier in charge of European relationships, and also direction of twenty master degrees and engineer degrees.

11. Training of LAAS Personnel

A number of needs previously identified from the “formation plan” have been satisfied thanks to the CNRS regional delegation “Formation” bureau and the lab’s investment. In the past 4 years, an average of 100 training actions par year have been followed by LAAS personnel (see Annex 2).

In terms of technical training, the personnel attended training sessions on the EMC of installations (15 persons) and Atomic Microscopy (5 persons). The technical services in the lab organize periodically training courses on the different micro-electronics and characterization technologies, software development, and robotics.

Hygiene and Security was one of the first priorities, with training on Laser safety and electrical habilitation for the concerned personnel, as well as gas safety. 28 first aid rescuers were also trained.

12. Hygiene and Safety

LAAS has set up the structures for informing and training the personnel on hygiene and safety issues and for preventing possible problems by targeted actions coordinated by the lab director. A H&S Committee composed of 13 persons is active and meets periodically with the CNRS medical service and the regional prevention agent. Given the size of the lab and the nature of the lab’s activities, two members of personnel have been named and trained as Agents for H&S (ACMO), and one member as radioprotection competent person (PCR) because of an X-ray generator and the ion implantation equipment. LAAS counts also 40 first aid rescuers of whom 28 were trained in 2008. They all have first aid equipment. Dedicated tools and specific information have been set up on the intranet, including the web application for risk prevention (EVRP) set up by CNRS in mid 2008 that we use to identify possible risks and follow the decided preventive actions. A registry for threatening and serious dangers has been set up. Specific risks at LAAS concern mainly the clean room and include dangerous gas and chemical compounds, high temperatures, and laser beams. All concerned personnel, including external users receive specific training.

13. LAAS 40th Anniversary: 40 years of scientific and human adventure

In 2008, LAAS has celebrated 40 years of existence. Numerous scientific events have been organized to celebrate this anniversary over the year. Two highlights, spanning the various research domains of the laboratory, were a Conference Cycle and a Scientific Workshop. Five distinguished speakers have contributed to the ***Conference Cycle*** as shown in the table below.

Dates	Speakers and Topics
May 28	**Joseph Sifakis**, Verimag, Turing Award 2007 *Embedded Systems: Scientific Challenges and Ways Forward*
June 20	**Jacques Stern**, ENS, CNRS Gold Medal 2006 *Cryptology: From Secret Messages to Electronic Transactions*
Sept. 8	**Pravin Varaiya**, UC Berkeley, USA, Nortel Networks Distinguished Professor *A Wireless Sensor Network for Traffic Surveillance*
VDec. 5	**Rodney Brooks**, MIT, Cambridge, USA Computers and Thought Award *Robotics: Shaped by and Shaping the World in 2000 to 2050*
Dec. 17	**Albert Fert**, UM de physique CNRS-Thales, Palaiseau, Nobel Prize in Physics 2007 *Present and Future of Spintronics*

The ***Scientific Workshop*** was held on October 7-9. Seventeen presentations by talented guest scientists and LAAS researchers, have reviewed the advances in the four research areas of the laboratory and highlighted the related challenges. The following table lists the contributing speakers.

AREAS	Speakers
MINAS	**Clivia Sotomayor** (Catalan Inst. of Nanotechnology, Barcelona, Spain) **Christophe Vieu** (LAAS) **Hervé Aubert** (LAAS) **Manos Tentzeris** (GeorgiaTech, Atlanta, USA) **Frédéric Morancho** (LAAS)
MOCOSY	**Germain Garcia** (LAAS) **Ioan Landau** (Gipsa lab.) **Erol Gelenbe** (Imperial College London, GB) **Jean-Marie Garcia** (LAAS)
SINC	**Jean-Claude Laprie** (LAAS) **Marc Dacier** (Symantec Research Labs Europe) **Michel Diaz** (LAAS) **Richard Castanet** (LaBRI)
RIA	**Jean-Paul Laumond** (LAAS) **Oussama Khatib** (Stanford Univ., USA) **Cynthia Breazeal** (MIT Media Lab, USA) **Rachid Alami** (LAAS)

The detailed program is available from LAAS website http://www.laas.fr.

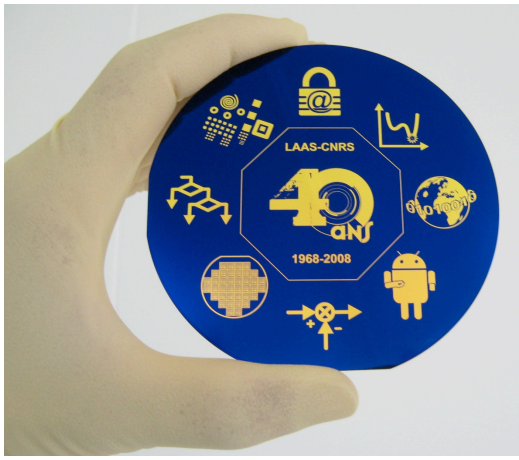

Figure 5. The 40th Anniversary Trophy, a silicon wafer realized in the laboratory, featuring icons suggesting LAAS' main research domains.

II. RESEARCH GROUPS SCIENTIFIC REPORTS

Research domain
MIcro and NAno Systems – MINAS –

Scientific Topics

For the past 15 years, LAAS-CNRS has been one of the major actors, in France, in the micro and nanosystem domain and has built up a unique expertise in that field. However, this area is now facing three major evolutions:

- the emergence of nanosciences which induces progressively the introduction of nanoscale materials or structures in devices and systems
- the need to make systems more and more complex by integrating multidisciplinary functionalities for detection, actuation and communication
- the spreading of micro and nano systems over a growing range of application fields, biology and health being one of the most promising.

Therefore, this evolution brings about profound changes that we have to anticipate:

- In the development of technologies where organic materials (structural and functional polymers, monomolecular grafted layers), 3D integration and bottom-up (self-assembly) nanopatterning technologies will be used more and more widely.
- In the development of modeling, simulation and design tools which have now to account for interdisciplinary and multiscale aspects.
- In understanding, mastering and integrating an increasing diversity of fundamental mechanisms.

Fitting to these major evolutions, the objective of the MINAS area is to propose original concepts and technologies in the challenging domains of distributed and autonomous systems and bio- medical applications. The key points are:

- The ***modeling and simulation of micro and nanosystems***. We aim at developing a virtual prototyping approach including reliability aspects. We propose also a multiscale and multiphysics approach for nano systems engineering enabling a close understanding and monitoring of molecular mechanisms.
- ***MEMS/NEMS and MOEMS***. The studies are dedicated to the development of sensing devices as well as of actuation systems and cover a wide range of applications from chemical or physical detection to active optics. Starting from Silicon technology, this domain is now widely opened to organic materials and in particular to polymers.
- ***RF and microwave systems***. Our contribution in this domain tends to develop miniaturized passive and active, reconfigurable RF devices and systems. The optimization of high quality microwaves sources and opto-hyper coupling is also at the heart of the activity which combines a strong contribution in CAD and design with technological efforts.
- ***Systems and devices for energy management***. This domain is driven by the challenging issue of power autonomy of portable systems. The activity is targeting four complementary topics: micro sources and energy harvesting, power integration and conversion, ESD protection.
- ***Nanophotonics and photonic integration***. The studies focus on the design and processing of advanced laser devices and encompass photonic bad gap structures. The activity targets also at integrating passive and active optics together with photonic sources.
- ***BioMEMS and Nanobiosystems***. This domains aims at exploring micro(nano)systems for biology as well as to exploit biology as a possible way to create new micro(nano)biosystems.

The Research Groups

The MINAS area gathers 7 research groups: ***Power management System Integration*** (ISGE), ***MIcro and Nanosystems for Communication*** (MINC), ***Systems Nanoengineering and Integration*** (N2IS), ***Microwaves and Opto microwaves for Telecommunication Systems*** (MOST), ***Microdevices and Microsystems of Detection*** (M2D), ***Nano Bio Systems*** (NBS), ***Photonics*** (PHOTO).

Facilities and platforms

The MINAS activity is strongly supported and closely connected to the technological facilities, characterization and CAD platforms which are supported by two technical (TEAM and 2I) services. The 1500m^2 clean room enables the manufacturing of semiconductor devices and micro/nanosystems from the early design of photolithographic masks to the final assembly. During the last five years, the RTB program has permitted to enhance significantly our technological capacities which combine standard Silicon technologies with polymers micro and nanofacturing techniques. The technologies we have developed cover all the application spectrum of our activity from MEMS to biodevices, through power integrated devices. These technical facilities are completed with a characterization platform based on high level instrumentations in electronics optics, RF allowing the test and characterization of materials, devices and systems. The CAD platform provides simulation tools and specific models allowing to analyse and understand the electrical and physical

behaviour of semiconductor devices and micro/nano systems in view of their design.

The Main Application Domains

The main MINAS objective is to bring a contribution in the field of:

- ICT and distributed systems
- energy monitoring for embedded and autonomous systems
- micro and nanosystems for biology, health and environment

90 senior researchers and 150 docs and post-docs are contributing to these mains topics, balancing their activity between long term research (ANR and FP6 projects) and collaborative projects addressing application goals with industrial partners. It is worth pointing out the coordination of the european network Of Excellence on RF MEMS and RF Microsystems ***AMICOM***. MINAS activity is also closely related to the regional research policy. Two projects are currently running in the frame of the "Pole de Compétitivité" Aeronautics, Space and Embedded Systems (AESE). LAAS has also been a major actor in the creation of the interdisciplinary Institute of Advanced Technologies for Life Sciences (ITAV). Three joint laboratories between CNRS and industrial partners are in progress.

Integration of Systems for Power Management – ISGE –

Permanent Staff:

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Objectives and positioning

Within the context of a sustainable development, some main issues regarding energy are related to the reduction of power consumption into buildings - over 40% of the primary energy consumption in Europe – and to the replacement of fossil energy in transports that will have to become driven-by-wire. In addition to the mandatory improvement of the conversion yield, the challenges of power management systems are in their required miniaturization, their evolution towards intelligent systems having energy autonomy and offering an increased robustness and reliability. To tackle these challenges, ISGE research group oriented its activities towards the design and integration (monolithic or multi-chips) of these systems for three main applications: building, transport-by-wire and ambient intelligence. For the two first applications, it is worth mentioning the convergence of technologies since voltages are in the same range (1200V). The goal is the development of the future generations of efficient and intelligent power switches. In the building, another challenge is the improvement of the power yield of conversion stages for solar panels by proposing innovative architectures. Finally, we started a new activity in the field of ambient intelligence, in cooperation with N2IS research group, on the issues related to energy harvesting as well as storage and power management. In France, our research group is the only one with G2ELab to address these integration issues, part of them being carried out in cooperation with this laboratory. Two other national laboratories, AMPERE and LAPLACE, LAAS partners in several projects, have complementary research activities in the field of power electronics systems and very high voltage devices. Internationally, we are in competition but also in partnership with CNM-Barcelona which specificity is SiC, the University of Cambridge (UK), the Fraunhofer Institutes (IISB and IMS) in Germany, Tyndall in Cork, CPES from Virginia Tech (USA) and from Rensselaer Polytechnic Institute (USA).

The challenges of power electronics integration are different from those of signal processing systems, given the large range of energies associated to each application (from mobile electronics to electrical traction) and the related high current and voltage levels. As a result, the design of new power devices and their integration requires a top-down approach starting from the application needs. Thus, ISGE strategy consists in a global analysis of the different aspects of the final system: converter architecture, active and passive devices, protection and robustness to propose innovative concepts and related technology solutions. This approach is supported by a strong expertise in the field of power system and electrothermal modeling. To tackle these new challenges of power integration, we have chosen to develop specific 3D technologies (deep trenches, double-side lithography...) to take advantage of the full silicon volume and of new physical mechanisms. Using new materials (magnetic, high-K dielectrics,..) in the silicon process is also a key step. Moreover, to fulfill the requirement of a higher switching frequency, we study new topologies based on interleaved structures and their digital control laws.

Highlights and Major Achievements

ISGE research activities are organized into four interdependent topics: Power Integration, Modeling, Energy conversion and ESD/EMI reliability. Moreover, some of these activities were carried out within the framework of a structuring industrial partnership of two joint laboratories, LISPA with Freescale and PEARL2 with ALSTOM and several aeronautics partners, thus allowing a successfull transfer of innovative research concepts.

"Power Integration" – Single or multi-chip integration is the main goal of all the studies carried out in ISGE group. As a consequence, an important part of our research activities is dedicated to the study of innovative power device structures and the development of specific technology processes for their integration. This includes active power devices (MOSFETs, IGBTs, bidirectional switches, specific functions such as self-switched devices based on MOS-thyristor structures or IGBTs) as well as integrated L and C passive devices.

Innovative Power Switches

Part of this work, carried out within PEARL2 joint lab (ended on November 2008) in cooperation with ALSTOM, consists in proposing integrated solutions of diagnostic and protection functions for a new generation of self-protected and reliable IGBT power switches that can be easily driven by standard circuits (Caramel thesis, 2007, Le Gal thesis) [ACL153].

An ambitious project carried out in cooperation with LAPLACE laboratory is the integration of a new self-protected and self-activated switch dedicated to current reversible static converters (F. Capy thesis), involved in systems using renewable energies, such as wind turbines or photovoltaic cells [ACL413]. The proposed self-switching mode devices can be considered as self-protected and do not require any auxiliary power supply, external drive circuit and sensor. They are autonomous and allow simplifying the topologies of the power converters. To this aim, we have chosen a thyristor-based circuit breaker, implemented within the same silicon substrate as its driving circuitry using the concept of functional integration. It includes a self-firing thyristor-MOS associated with its control and driving devices. The design, based on the intensive use of 2D finite elements simulation, is now completed and shows that the electrical behavior of this topology is very efficient. An alternative solution based on an IGBT was also investigated: it is built up from an IGBT with sense emitter cells and a self powered supply. Each elementary block (IGBT-sense, 3D capacitor and MOS) was separately validated on silicon and the full process integration is currently being carried out [ACTI1538] [ACTI1346].

Another challenging project concerns the design and realization of a bidirectional (both voltage and current) IGBT switch, project carried out in collaboration with LMP-Tours and G2Elab-Grenoble (MOBIDIC ANR project). The concept is based on the monolithic integration of two IGBTs on both sides of a silicon wafer using the Si/Si wafer bonding technique [ACL265]. The monolithic integration of these two structures would allow, through an adequate control strategy, the reduction of the power losses, the silicon die area (as compared to the use of two discrete IGBTs) and the components number count. The integrated device requires a symmetrical blocking voltage capability that can be achieved using specific peripheral junction terminations such as P+ wall through silicon wafer, based on a combination of deep RIE of silicon and deposit of boron-doped polysilicon. This key process step was validated in a previous project. Over this period, we worked on the optimization, through 2D simulations, of the device structure and validated the integrated device operating principles. We also studied the impact of the quality of the bonding interface on both static and dynamic device performance. Concurrently, we developed a suitable technology process that could be integrated in the classical IGBT process flow and the device realization is now being carried out.

Regarding the currently advances achieved in wafer thinning techniques (less than 100 um thick wafers) and the obtained results on the quality of wafer bonding, the reduction of the wafer thickness and then of the on-state losses should be achieved.

In low and medium voltage power applications (breakdown voltage below 600 V), the power MOS transistor is the preferred switch. The main challenge is the trade-off between specific on-resistance ($R_{ON}.S$) and voltage handling capability (BV_{DSS}), which is limited by the silicon properties. Over the last decade, several MOSFET configurations have been proposed to overcome this physical silicon limit: Trench Lateral MOSFETs, Floating Islands MOSFETs (FLYMOSFETs) and Superjunction MOSFETs (SJMOSFETs). All these concepts have successfully demonstrated the improvement of the "$R_{ON}.S$ vs. BV_{DSS}" trade-off, and were implemented in commercial devices such as the CoolMOS™ and the LUMOS. The contribution of ISGE group in this area is particularly remarkable since it was the first laboratory to propose two of these new concepts (Trench Lateral MOSFETs, Floating Islands MOSFETs) [ACL90].

To get a significant improvement, we developed the Floating Islands concept: it consists in introducing one (or several) P^+ floating island(s) between drain and source to either increase the voltage handling or decrease the on-resistance. Within LISPA joint lab (Y. Weber thesis), 200V FLYMOSFETs with two floating islands between drain and source were fabricated for the first time in 2007. The best structure exhibits state-of-the-art static and dynamic performance compared to the best commercially available structure i.e. the 200V SJMOSFET. Dynamic characteristics (switching losses, switching time) are similar, whereas the on-resistance value, of $4.5 m\Omega.cm^2$, is improved by 45% and overcomes for the first time the theoretical silicon limit. Furthermore, regarding the dynamic behavior, compared to the SJMOSFET, the "$R_{ON}.Q_g$" figure of merit of the FLYMOSFET is improved by 25% [ACTI1131].

Regarding SJMOSFET devices, we proposed an original process solution based on a deep trench technology (L. Théolier thesis). Key technological process steps (deep reactive ion etching -DRIE-, trench filling with BenzoCyclo-Butene -BCB- and Chemical Mechanical Polishing -CMP-), were validated in 2008 by the fabrication of a new junction termination (Deep Trench Termination, called DT2), consisting in a 70µm-wide and 100µm-deep trench:

the technological process is relatively simple and could be used for the realization of a wide variety of high voltage power devices. Experimental data show that this new junction termination sustains 1300V with a leakage current of 10 µA/cm^2 [ACTI1524]. Furthermore, the width of the DT2 being only 70 µm (Fig.1), the junction termination area is dramatically decreased compared to conventional junction terminations in this voltage range (200-300 µm width).

Figure 1: Deep Trench Termination (DT2) after filling with BCB and CMP at the surface.

Finally, within SPOT2 MEDEA+ European project (G. Toulon thesis), we successfully designed 150V power LDMOSFETs for an advanced smart power technology on thin-film silicon-on-insulator (0.18 µm SOI-CMOS technology from ATMEL) [ACTI1547].

Integrated passive components

The ever-reducing size of electronic hand-held equipment combined with the increase in the numbers of functionalities, arises a blocking point relative to the power management of the system. DC-DC converters will have to adapt to these new power requirements while being miniaturized and improved in terms of efficiency, cost and reliability. Passive components assuring storage and filtering (i.e. resistors, capacitors and inductors) are the bulkiest components of the systems. For low power applications (typically few watts), increasing the operating frequencies allows the size reduction of these passive components and thus the integration on silicon/glass substrate using microfabrication techniques. The challenge for these new types of components is therefore to allow a high power density while minimizing losses at the operating frequency.

Our research efforts have been focused for more than 10 years now on the integration of inductors on silicon for DC-DC converter applications. The difficulty is twofold: first, depositing thick conductors to reduce conductive losses and secondly, integrating into the component a thin-film magnetic material with high resistivity, high saturation magnetization, high in-plane anisotropy field. Similarly, high-density integrated capacitors have been developed with a particular emphasis on the optimization of the structure geometry: reduced dielectric thickness, enhanced electrodes area or the use of thin-film dielectrics with a high permittivity.

Regarding microinductors, we developed an electrochemical deposition process for $Fe_{25}Co_{60}Ni_{15}$ magnetic material. We successfully fabricated a 1µH "spiral type" microinductor stacking three 40µm thick material layers [ACTI1122]. The lamination of the magnetic core allows reducing the eddy current effects. The air gap increases the stored energy capabilities and prevents the saturation phenomenon. This device was characterized in a 2MHz test converter with a 0.6A peak current.

Regarding integrated capacitors, technological processes were developed with the objectives of reaching very high capacitance densities (500 nF/mm^2) and very low losses. Within the ANR project "Camino", two approaches were combined: high electrode surface area provided by high density pores networks etched into silicon and the use of high-k dielectrics. We successfully performed 3D surfaces into silicon using two different techniques: deep reactive ionic etching (DRIE) and electrochemical etching (INL, Lyon). The capacitance density of the realized 3D capacitors using DRIE and SiO_2/Si_3N_4 dielectric, reaches 60 nF/mm^2 up to 5 MHz operation frequency, with less than 200 mΩ of series resistance [COM30]. Using electrochemical etching allowed producing a dense nanopores network with very high aspect ratios (123). The resulting capacitance density can be as high as 650 nF/mm^2 and the component thickness is limited to 100 µm, which is of major interest when 3D integration with other components (such as active components) is considered. In collaboration with LEHME at Orsay, the development of MOCVD-deposited high-k ZrO_2 dielectric was achieved. The deposition conditions were optimized to obtain the tetragonal phase of the material that exhibits a higher permittivity than the monoclinic phase usually obtained in the literature [ACL610]. The ZrO_2 layer showing a permittivity of 27 will replace the SiO_2/Si_3N_4 in future capacitors.

"Energy Conversion" – This activity is focused on the validation of innovative concepts and functions aimed at significantly improving the efficiency of power conversion systems, from power sources to DC or AC loads with, eventually, intermediate storage stage using electrochemical batteries. Since several years, one main applicative field is related to renewable energies, and more particularly the solar one, in strong cooperation with French industrial companies (EDF, TOTAL, SAFT and CEA). Moreover, within LISPA, Freescale-LAAS joint lab, we have developed new "low voltage-high current" conversion architectures for the power management in portable and embedded applications. Regarding low voltage applications, we addressed the challenges of high frequency (few MHz) DC-DC converters. We proposed and validated, both with DSP and FPGA-based approaches, new digital

control laws, compatible with these frequencies and multiphase architectures [ACL486] [ACTI1132].
In both applications, the main strategy consists in implementing distributed and multi-phase architectures with their related driving and control laws. The objective is a significant miniaturization of the system through the increase of switching frequencies.
In 2007, the activities dedicated to photovoltaic (PV) conversion were focused on the development of new concepts for "PV Electronic Modules" such as the power gyrator that allows easily solving the parallelization of converters [ACL239]. In addition to the proposed innovative theoretical approach carried out in tight collaboration with Tarragona University (URV), this study on the discretization is currently continuing within Microscope project coordinated by EDF, the French electricity energy leader. This work (Cid Pastor thesis) was awarded 3 times: club EEA-section électrotechnique, Paul Sabatier Award from Académie des Sciences et Belles Lettres of Toulouse and best engineer thesis from UPC-Barcelona.
Nowadays, our research activities are oriented towards the increase of the energy production that is, maximizing the power obtained from the PV module terminals. Right now, the literature proposes a large number of control algorithms to continuously track the Maximum Power Point (MPP) [ACL126]. However, a limited number of solutions are proposed to improve the global efficiency of the conversion chain. Therefore, we have been carrying out several studies, first, on the development of new adapted control laws using extremum seeking controls (in cooperation with MAC research group at LAAS and the University Rovira I Virgili, Tarragona, Spain), and, second, on their innovative implementation using low consumption techniques. Two thesis have been defended (C. Cabal and S. Petibon), one supported by the ANR Microscope project and the other by the ANR ATOS project, coordinated by the LPICM (Palaiseau).
Moreover, to solve the problems due to the intermittency of PV energy production, new studies have been started in 2007 on innovative energy management strategies to store and restitute energy with high efficiency. Part of this work is carried out within the framework of Li-PV ANR project coordinated by the CEA-LITEN.

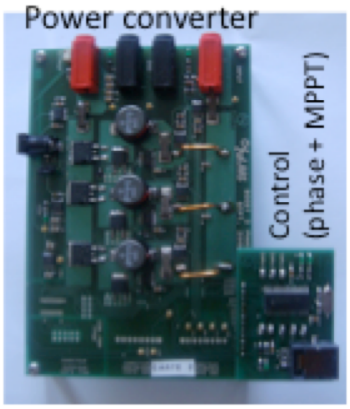

Figure 2: Adaptive 3-phases boost converter allowing increasing the efficiency from 86% to 92% compared to a single phase one.

"ESD/EMI" - Our activities in the field of electrostatic discharges (ESD) were initially focused on the design of innovative integrated protections with strongly improved performance. We recently broaden them to system level ESD through the modeling of the impact of ESD stress on a printed circuit board, as well as to a material approach in collaboration with the Laboratoire de Chimie de Coordination (LCC-Toulouse) to develop "above IC" integrated varistances. Most of these activities are carried out in tight partnership with industrial companies thus allowing the validation of innovative concepts on advanced technologies.
In particular, within LISPA joint lab, three projects have been carried out. The first one, related to integrated ESD protections, was dedicated to the development of a simulation methodology based on a physical approach to predict the robustness of an ESD protection [ACL211] (Salamero Ph.D. thesis). This predictive methodology has been applied to propose a very efficient ESD protection solution using PNP bipolar transistors for high voltage (100V) smart power technologies: on-resistance < 1ohm and failure current > 5A [ACTI546]. This protection strategy was patented and is now implemented on commercial products (Gendron Ph.D. thesis). The Ph.D. student was hired by Freescale-USA for the related technology transfer and continues collaborating with LAAS-CNRS within the framework of a new Ph.D. thesis focused on the study of the triggering dynamic behavior of ESD protections (Delmas Ph.D. thesis). The second LISPA project was related to system level ESD, and was also funded by the French Defense Agency. We proposed an original characterization methodology based on a vf-TLP test bench (pulses<10ns) as well as the modeling of the ESD stress propagation using VHDL-AMS (Lacrampe Ph.D thesis) [ACTI1004]. This way, we were able to correlate measurements and simulation results of the upset of an operating microcontroller induced by an ESD stress. The third LISPA project was related to an innovative material approach. LCC proposed a new synthesis method for ZnO nanoparticles and the introduction of additional elements such as bismuth. It was demonstrated (L. Saint Macary thesis) that pellets fabricated by flash sintering in cooperation with CIRIMAT exhibit a varistance behavior [ACL602], which allows contemplating their integration onto silicon.
In addition to these studies, we also focused our activity on the impact of ESD stresses such as the Charged Device Model (CDM) one. Such stress originates from the charging of the IC itself and its discharge through a single pin. As a result, currents are flowing over the whole chip and it is particularly

difficult to model the discharge paths and then to optimize a protection strategy. Two theses were dedicated to these studies. First, Nicolas Guitard thesis studied the impact of CDM stress on the generation of latent defects. He demonstrated that low frequency noise measurement could be successfully used to detect them [ACTI1031]. Second, Yuan Gao thesis confirmed these results on a complex circuit (DC-DC converter). She also proposed an original modeling approach of the IC substrate that allows predicting with a better accuracy the CDM discharge paths.

Finally, in cooperation with MINC research group at LAAS, we have started a new activity regarding the ESD robustness of RF MEMS structures (J. Ruan thesis). The first results allowed understanding that such devices require a specific approach compared to integrated circuits. Appropriate characterization methodologies and dedicated protection strategies are currently under development.

"Modeling" – Over the last years, we have oriented the modeling activity towards the development of predictive tools dedicated to the improvement of power devices reliability that is required to tackle the challenges of power integration and high temperature. Regarding the electro-thermal modeling, an important breakthrough concerns the development of an efficient methodology for the extraction of simple compact thermal models that take into account non-linearities and 3D effects. They allow simulating an unspecified number of heat sources and cooling surfaces with an adaptive procedure depending on boundary conditions (W. Habra Ph.D. thesis). We are still working on compact thermal modeling, as we have to extend the developed models to transient mode with multiple heat sources and multiple cooling surfaces [ACTI1438].

Within PEARL joint lab, we studied the behavior of power chips, IGBT and diodes, which have to withstand a large range of temperatures, especially in aeronautic applications. The objective is to choose the most robust technology with the help of physical modeling and measurements. To this aim, we have set up a measurement test bench for the extraction of static and dynamic parameters for temperature ranging from -55°C to 150°C [ACL525].

Within LISPA joint lab, in collaboration with CEMES lab and M2D group at LAAS, we developed characterization tools for accelerated ageing. A related thermo-mechanical modeling for a predictive reliability approach has been achieved.

This study allowed proposing an efficient modeling approach together with the accurate extraction of physical parameters for various thin-film materials that we applied to the predictive analysis of the reliability of power devices assembly (JB. Sauveplane Ph.D. thesis) [ACL364].

Moreover, within ELIAS European project, we develop a simulation tool coupling electrical and thermal modeling for power MOS devices operating under strong current pulses. This project is progressing in close cooperation with Epsilon Company, and will contribute to improve the Rebeca-3D software developed by this company.

The Predit program EPO-AUTO gives the opportunity to the LAAS to develop new collaborations with INRETS and VALEO. We could support the various thermal cycling tests on different technologies of power MOS and IGBT for automotive application by adequate electrothermal modeling [ACTI1295].

Finally, in cooperation with EADS-France (A. Lu thesis), we started a new activity dedicated to the hardening of IGBT modules against heavy ions irradiation for aeronautics. We demonstrated that coupling physical simulations of the power devices to measurements via laser stimulation provides a better understanding of the involved physical mechanisms, essential step to propose efficient hardening solutions. The first results were awarded by the "Best Student Paper Award" at RADECS [ACTI1247].

Significant projects and collaborations

Joint labs:

PEARL2: Power Electronics Associated Research Laboratory – ALSTOM, 3 research projects, cooperation with Hispano-Suiza and CNM-Barcelona.

LISPA: Laboratoire d'Intégration de Systèmes de Puissance Avancés – Freescale Semiconductor, 6 research projects, collaboration with Laboratoire de Chimie de Coordination, CIRIMAT and URV Tarragona University.

AIRBUS cooperation: SACER and AUTOSENS national projects: energy autonomy issues of wireless sensors.

ANR projects:

ATOS: Associations Tandem Optimisées pour le Solaire – cooperation with CEA.

MICROSCOPE: Micro Injecteur Connecté au Réseau pour Optimiser par le Stockage la Courbe de Production Electrique – cooperation with CEA.

LIPV: Module multifonctionnel stockage Li-Ion et conversion Photovoltaïque de l'énergie solaire - cooperation with CEA.

CAMINO: Eléments Capacitifs MIM à forte densité Intégrés sur Silicium pour la conversion de l'énergie – cooperation with INL-Lyon and LEMHE –Orsay.

MOBIDIC: MOS controlled BI-Directional Integrated power Component - cooperation with G2Elab

European projects:

SPOT2: Deep Sub-micron Smart-Power Technologies - MEDEA+ project, cooperation with ATMEL-Rousset.

ELIAS: End-of-life investigations for automotive systems - MEDEA+ project, cooperation with Epsilon.

TARGET: Top Amplifier Research Groups in a European Team - FP6 European Network of Excellence.

Micro and Nanosystems for wireless communications – MINC –

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Objectives and positioning

It is now understood that wireless communications are playing a major role in many industrial and societal sectors and this increasing emergence turns out to the necessity to anticipate the future technologies and architectures that will be used from 5 to 10 years. The wireless communications are not seen as a medium to handle speech, voice but as global medium able to handle heterogeneous versatile data from different places and using less and less energy resources. In this context, it appears that we need to better understand and assess the electromagnetic spectrum with an optimized efficiency and enhanced robustness. This has motivated the creation of the group Micro and Nanosystems for Wireless communications in January 2006 considering the need to anticipate the new wireless wave that is arriving. In Europe this has been anticipated under different issues. During FP6 numerous initiatives have been launched (Network of Excellence AMICOM, Integrated projects MIMOSA, e-Cube, and numerous STREP projects supporting research aiming to introduce new functionalities within wireless platform. In FP7, this has been consolidated mainly through two European platforms:

- European Platform on Smart Systems (EPoSS, www.smart-integration.org) where introducing intelligence within wireless architectures to form smart systems is a very important part of the strategic agenda
- ENIAC platform (www.eniac.eu) where the RF MEMS technologies are cited as high potential candidate for future wireless modules and where it is also mentioned the importance of the concept of wireless sensor network.

In United States, there is also intensive research supported by NSF, DARPA concerning this field and the major centers (Georgia Tech, Berkeley University, Virginia University,…) are involved in exploring new technologies and architecture for wireless communications and sensor network. Japan is also considering this field as very important and is referred to as "Internet of Things".

Taking into account the aforementioned issues, it has been decided to orientate the research toward the **"electromagnetic energy engineering from nanoscale to system level"** that is to our knowledge quite original in the scientific community.

The research activities that have been conducted propose to explore **innovative solutions to introduce «intelligence» within wireless architectures both at analog and digital level**. The objectives that are foreseen deal with research at material, device and system level. They combine theoretical and technological developments, modeling, simulation, design and advanced instrumentation. **The research activities that have been done were driven by applications in the field of defence, aeronautic, space and automotive**. During the period, the activities have been organized following the eight topics listed below:

- Smart materials (ferroelectric, ferromagnetic, metamaterial, piezoelectric…)
- Reconfigurable devices and circuits
- Innovative devices
- RF MEMS reliability
- Multi-physic modelling
- Electromagnetic simulation of complex systems
- System modelling
- Wireless sensor network

Finally, it has to be outlined that this strategy is aligned with the activities that were conducted within a Network of Excellence (AMICOM, www.amicom.info) that was coordinated by the LAAS-CNRS.

Highlights and Major Achievements

The 2006-2008 period has been the infancy of the research group and this has resulted to an increasingly activity on a very large scientific spectrum involving new interdisciplinary collaborations with physicians, chemistry and computer science searchers with numerous results that will be briefly assessed in the following:

Smart Materials

The vision and the approach that has been implemented deals with the exploration of potentialities of materials themselves (i.e ferroelectric, ferromagnetic, multi-ferroic, piezoelectric) or the potentialities resulting from appropriated micro and nanostructuration (i.e metamaterial). Among the results, we have demonstrated the very attractive capabilities of BST material for reconfigurable resonator with tuning range larger than 60% and high quality factor in the range of 50 @ 30 GHz. Other results have been obtained on LSMO materials featuring interesting tuning range at RF frequency. Concerning piezoelectric material, the main activity has concerned their mechanical and electrical properties with the development of specific test set.

Reconfigurable devices and circuits

This activity deals with the RF MEMS process development where significant progress have been achieved with a better understanding of the origin of strain and gradient of strain that has allowed to propose some appropriate annealing to minimize dramatically the strain in MEMS membrane as illustrated in figure 1 and to be able to propose more flexibility to the designers.

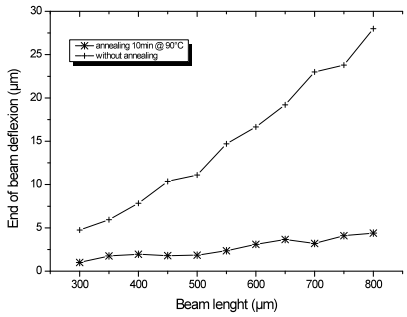

Figure 1: Measurements of a beam deflection with respect to beam length and different technological process

This result has made possible the development of a scalable library of shunt switch from 20 GHz and 94 GHz and the development on the same process of both capacitive and ohmic switch (Fig.2) that opens very interesting opportunities for the design of RF MEMS based systems.

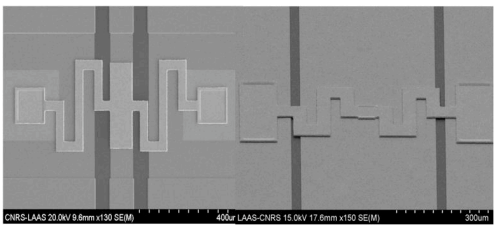

Figure 2: Ohmic and capacitive switch fabricated on the same wafer

Concerning the design and the modeling, numerous results have been obtained. The first one deals with the demonstration of the RF MEMS capabilities to optimize the electromagnetic resources through a reconfigurable PAE with respect to the output power of an RF power amplifier. Others devices have been fabricated concerning 20 Ghz high power tuner, tunable filter at 60 GHz, 94 GHz as illustrated in figure 3 and phase shifter at 60, 77 GHz using the scalable model developed and featuring very low insertion loss at the state of the art.

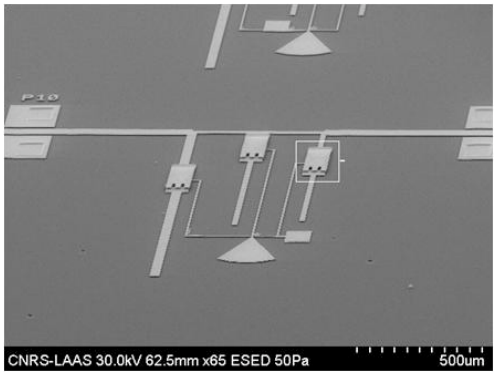

Figure 3: Tunable filter @94 Ghz

Innovative devices

Different types of innovative devices have been demonstrated during the period. The first type of device is referred to as nanotechnology enablers for RF devices. In this context, it has been demonstrated the coupling between carbon nanotube carpet and coplanar wave guide that has shown a very sharp resonance frequency in the 1.4 GHz range. Additionally, the carbon nanotubes have been inserted into different microwave cavity and they have shown very interesting behavior (i.e increase of the quality factor of a BAW resonator or possibility to develop highly sensitive gaz sensor, increase of the RF MEMS reliability or improvement of the thermal conductivity of CPW). Additionally, it has been shown theoretically that combining MEMS and NEMS (using CNT) it will be possible to develop advanced miniaturized power meter ranging from µW to W. It has been also demonstrated theoretically that using the carbon nanotube in a particular arrangement could be used to propose new approach for RF energy scavenging. Some works have been initiated concerning graphene potentialities and we have shown theoretically that it could be a very attractive alternative for millimeterwave switch with low insertion loss and high isolation with moderate actuation voltage (20V). The second type of innovative devices that have been demonstrated deals with the electromagnetic energy engineering. The first device is a three band miniaturized antenna (Galileo, GPS, MicroSAT) with an original feeder as plotted in figure 4.

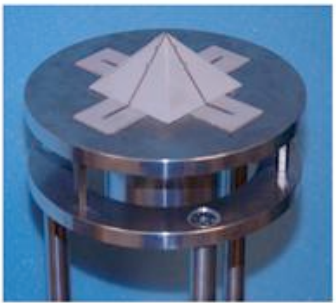

Figure 4: Multi band antenna for space applications

In this field of electromagnetic energy engineering and more precisely in the context of optimization of energy resources, we have developed an original broadband repeater (See Fig.5) that has demonstrated an improvement of the Bit Error rate from 10^{-6} to 10^{-9} that is very important in the context of wireless systems in embedded environment.

Figure 5: Photography of the broadband repeater fabricated

Another category of innovative devices deals with the development of microwave devices using Substrate Integrated Wave Guide Technology where we report compact coupler, phase shifter and metamaterial featuring advanced performances. It has to be outlined that a demonstration of reconfigurable filter has been done using defect ground structure on CPW. Finally, the last category of device deals with the demonstration of reconfigurable scatterers that will be used for micro-sensors identification (note that the activity of mmwave sensor is reported in the M2D group section).

RF MEMS reliability

We have adopted an original approach based on the Physic of Failure from material level to device level. In this context, it has been developed different characterization methods and models to get a better insight concerning the degradation mechanisms (more precisely the dielectric charging) occurring in RF MEMS devices and limiting their industrial diffusion today despite their fantastic capabilities.
To investigate the dielectric charging foundations, we have developed a method an AFM/EFM method that allows to investigate the charging kinetic as plotted in figure 6.

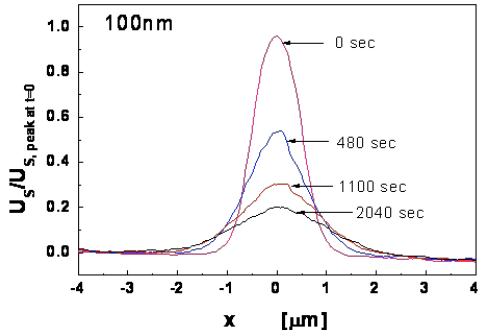

Figure 6: Charge distribution measured using AFM/EFM method

Another approach deals with the exploration of dielectric charging in MIM capacitances using different electrical and physical spectroscopy. Among the major results we can stated that we have observed a strong influence concerning the way the dielectric is elaborated (i.e the plasma frequency, thickness layer, type of dielectric). It has been identified the trapping characteristics versus dielectric thickness as plotted in figure 7 where it shows that a thin dielectric will be strongly affected by long charging process when a thick dielectric will be affected by slower processes.

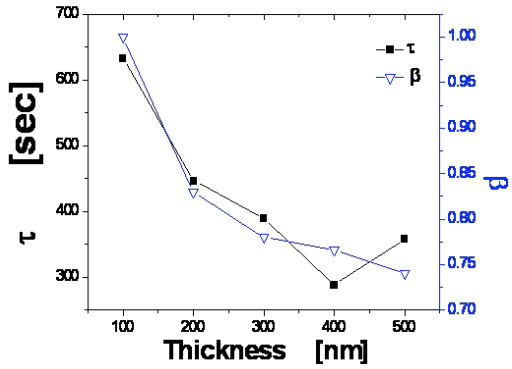

Figure 7: Evolution of the time constant of trapping effects versus dielectric thickness for SiN layer

Other results have shown that the stoechiometric composition has a significant influence on the dielectric charging and that the Si-H bonds were involved in the degradation mechanism processes.
Finally, it has been developed a test set and a methodology to stress real RF MEMS devices. This test set has been transferred to industry (Thales Alenia Space) and is very useful to qualify the different RF MEMS technologies. At LAAS, the test set has been used to develop some models of degradation where through a Poole Frenkel law (note that VHDL model of dielectric charging has been developed and is reported in the N2IS section). Finally, we have been among the first investigating the sensitivity of RF MEMS with respect to ESD shows that ESD protection should be carefully addressed (note that some works will be also reported in the ISGE section).

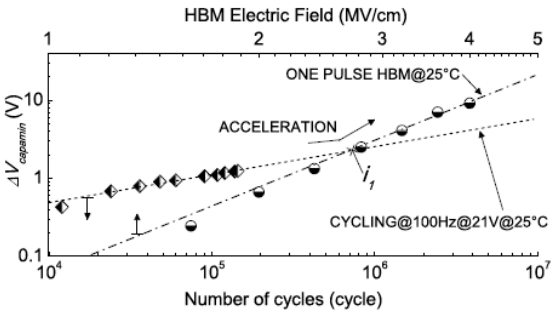

Figure 8: Evolution of voltage actuation versus cycling and HBM pulse

The most important results is displayed in figure 8 where we have found that HBM stress could used as accelerated method (one pulse producing 48000 cyles) for aging that has been never observed.

Multi-physic modeling

The activities that have been carried out during the period concentrates on the simulation of the contact properties of RF MEMS devices taking into account the roughness of the contact. A simulation platform has been set up to describe precisely the contact properties of an ohmic switch. As an example, figure 9 shows the contact properties of a MEMS device with respect to contact force.

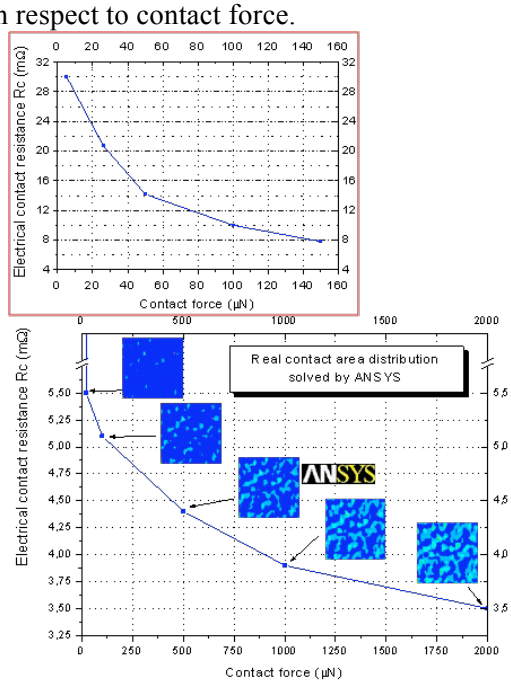

Figure 9: Contact resistance versus contact force for an RF MEMS

The second important result that has been achieved during the period deals with the set up of a test set allowing a precise measurement of the temperature distribution of a RF MEMS together with appropriate electromagnetic and thermal simulation using both HFSS and e-Physic platform. Results are summarized in figure 10 and have shown very good agreement and will be very efficient tool for designing RF MEMS handling high power values.

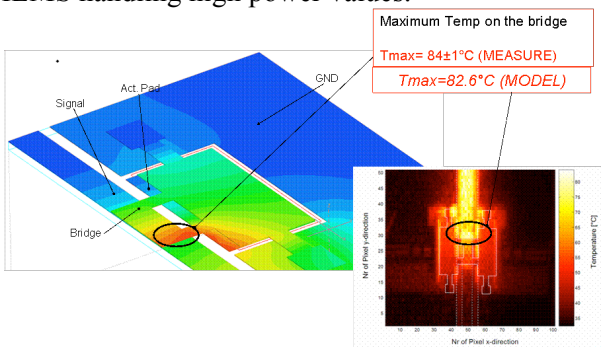

Figure 10: Simulation and measurement of temperature distribution for a RF MEMS device

Electromagnetic simulation of complex systems

In this topic, we are developing new methods, new algorithms to be able to address the electromagnetic simulation of complex structures. Fig.11 shows an example of a RF MEMS based reflect array that is modeled and simulated using the scale changing method developed in house.

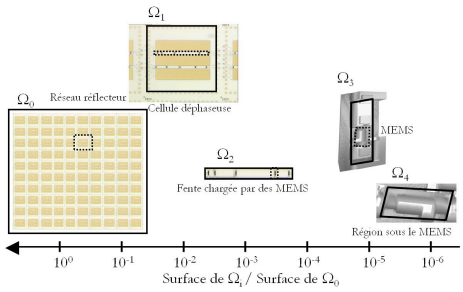

Figure 11: Presentation of the scale changing method applied to a RF MEMS based reflect array

This method is translating to a significant reduction of the computation time and an improvement of the convergence computation. This is used to investigate the sensitivity of reflect array architecture with respect to technology dispersion. When the structures are more complicated (3D), we have coupled this method with an open source 3D TLM method (www.yatpac.org). In order to be able to assess more complex structures, the two methods have been successfully implemented on the computation GRID architecture (ie using the GRID 5000 initiative).

System modeling

This section addresses system modeling both in the analog and digital range. The first category of results concern the analog domain where it is has been developed a specific design methodology based on neurons network for millimeter wave circuits that is to our knowledge very original followed by a set of VHDL-AMS library of RF MEMS devices and RF MEMS based phase shifters that is also to our knowledge the first demonstration. The second category deals with an FPGA enabler that has been developed through a reconfigurable multiband IR-UWB architecture (i.e modulation scheme, BER,

frequency band, localization). Both IR_UWB emitter and receiver have been implemented on this FPGA platform and some ASIC have been designed and fabricated (see Fig.12).

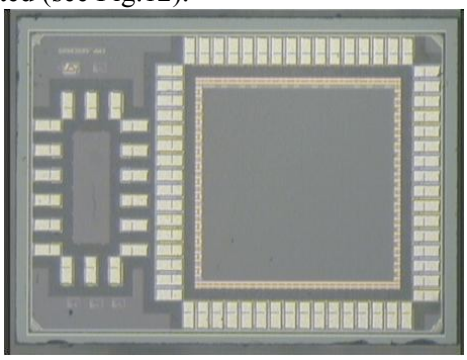

Figure 12: 1 bit and 8 bit IR-UWB emitter design using 65nm CMOS process from ST microelectronics

Wireless sensor network

This section deals with the research of architecture aiming to develop miniaturized wireless sensor network able to operate in harsh environment and being as autonomous as possible. Two approaches are addressed. The first one deals with the use of purely passive sensors that are read through a FMCW radar (using the concept of radar cross section coupled to the physical quantity). A radar has been assembled (in the millimeterwave range) allowing the detection of targets of 2cm^2 diameter at 20 meters. Note that innovative reconfigurable scatterers have been proposed that makes possible both the identification and the read of the sensors that has been never done so far (an example of the different RCS achieved is given in figure 13).

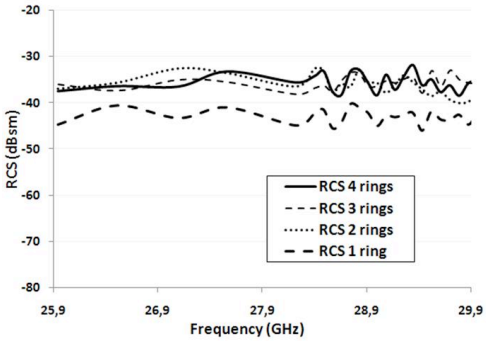

Figure 13: Example of radar RCS measurements using different reconfigurable targets

The second approach is more conventional and deals with the development of transceiver connecting the sensors. In order to accommodate with energy, interferers requirements, it has been chosen to concentrate on IR-UWB architecture in the 6-8 GHz range and 60 GHz range. Note that the based band architecture will be common and all the circuits will be fabricated using 65nm CMOS process. It has to be emphasized that for the 60 GHz range, the architecture will involve miniaturized antennas including MEMS RF in order to optimize the electromagnetic resources through 3D assembling techniques.

The main results obtained during the period concern the development of a reconfigurable based band architecture supporting different modulation schemes, supporting RF MEMS based antennas (including their control functionalities). An UWB platform has been set up using COTS components. Finally, the entire network has been simulated taking into account all the previous parameter using Globosim simulator.

Significant projects and collaborations

During the period, we have been involved in numerous research projects (10 ANR projects, 7 FP6, 2 from industrial clusters and 2 scientific foundations. In figure 14, we give an example of the ANR projects we have been involved with.

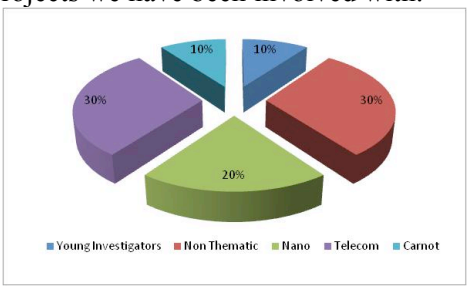

Figure 14: Distribution of the different ANR projects

It has to be emphasized some projects resulted from pluridisciplinary research with chemistry laboratories, physics laboratories and computer science laboratory and have concerned new research topics.

On the industrial level, we have been involved in two important projects. The first one concerning the development of a low actuation voltage RF MEMS with LETI and Freescale and the other one concerning wireless sensors network for aeronautic and space (SACER) project with AIRBUS and five SMEs.

Concerning the European collaborations, our main contribution for the last period has been the coordination of a Network of Excellence (AMICOM) that has translated to the creation of an association for sustainability issues and by the creation of a CNRS European Joint Laboratory (Smart MEMS) with IMT Bucarest (Romania) and IESL Forth (Greece). During the period it has to be outlined that each year we have had a long term visiting professors (between 6 months and a year) from Romania and Greece.

On the international level, three main collaborations have been initiated with Toronto University on the development of smart transceiver at 160 GHz, with Georgia Tech on the development of microwave circuits on paper and with Taiwan on CNT based RF system on chip.

Nano Ingineering and Systems Integration – N2IS –

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Long term visitor: E. Campo

Objectives and positioning

Aware of the opportunities driven by nano technologies and their potential impact on microsystems and their system applications, with the approval of the LAAS management, we changed the acronym of our group. On February 17 2008, MIS (Micro Integration System, created in 1998) has become N2IS for "Nano Ingénierie et Intégration Systèmes" in French, or "Nano Engineering and Systems Integration" in English.

The strength and specificity of our research group is to share expertise relevant for the design of new micro and nanosystems from the atomic level up to the systems level. Two alternative approaches are usually followed, either design and fabricate systems using glass, polymer or silicon micro/nanomachining at the LAAS clean room facility, or take from the shelves and architecture systems to implement new functions.

Three main challenges have been addressed:

• We developed original and high-performance technological approaches enabling:

- the 3D integration of full polymer or heterogeneous (Si/polymer) [ACL321] [ACL418] [ACL452] [ACTI916] [ACTI920],
- the integration of nanoscale functionalized materials for fluidics, optics and energetic applications [Bre12] [Bre13] [ACL16] [ACL35].

Our expertise in atomic scale simulation is an essential lever of our activity because it provides a rational understanding of manufacturing processes that guides their optimization and sometimes gives hints to elaborate new functions.

• We proposed and implemented new concepts and methods for point of care diagnosis and fundamental biology by way of micro/nano fluidic systems.

• We devise new embedded microsystems dedicated to pervasive networks focused on structural and health monitoring (monitoring of elderly and structural aircraft monitoring).

Highlights and Major Achievements

Based on an integration objective, we mapped our research activity into four major complementary scientific and technological topics:

• Atomic Scale Modeling and Simulation
• Advanced MEMS
• Micro-nano fluidics integration
• Systems for Structural and Human Health Monitoring.

Atomic Scale Modeling and Simulation

Our challenge is the predictive modeling dedicated to atomically precise technology for the following topics:

- ⇨ oxidation (Si, SiGe), growth and self assembled monolayers [ACL400]
- ⇨ biomolecular interactions [ACL539]

For non biological systems, we have developed multi-scale strategies combining ab initio, kinetic Monte Carlo and mesoscopic modelling tools. For biomolecules, we have developed a new treatment of molecular flexibility (Static Modes) which is based on the concept of "induced-fit" and authorizes the blind prediction of the conformational response of a molecule submitted to an external excitation. The approach is validated on the protease HIV-1 and constrained DNA [ACL52] [ACL156] [ACL210] [ACL258] [ACL285].

During this period, our main achievements are :

- inorganic materials: Si oxidation, Ge condensation, SnO2 surfaces for sensing, High-k materials deposition, Si nanodots [ACL298][ACL305].
- organic/inorganic interfaces: PNIPAM molecules and SAMs (Self Assembled Monolayers) [ACL300] [ACL376].
- Biomolecules: development of Static Modes, Free access to static modes on a web Data Bank (www.laas.fr/FLEXIBLE) [ACL339] [ACL351].

- Software produced: FLEXIBLE, HIKAD & OXCAD (transferred to CEA DAM), Sn02_CAD.

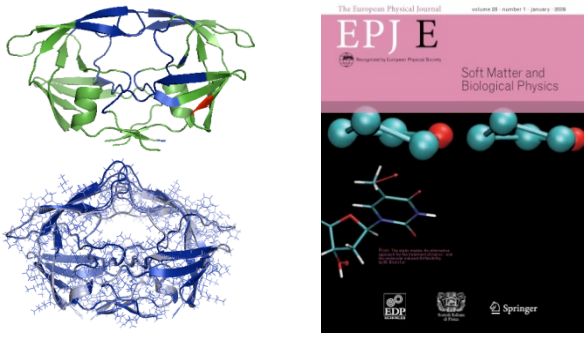

Figure 1: (a) Opening/closing movement of the flaps (b) cover of EPJ January 2009

Partnerships:

- *Inside the LAAS:*
  gas sensing modeling (M2D partnership); biomolecular interactions (RIS), PNIPAM (N2IS),
- *National level:*
  Establishment of a joint research team (ERC: Equipe de Recherche Commune) with CEA DAM, CEA-LETI (nanodots), LPPM-Orsay (oxidation)
  - ANR : OSIGE-SIM, LN3M, Jeune chercheur, NANOBIOMOD, ITAV ALMA
- *International level:*
  - Finland: ALEBOND (VTL)
    US: CNRS-NSF (Rutgers University); University of Texas Dallas, University of Southern California.

Advanced MEMS

This research axis is the think tank for the development of MEMS-based multi-functional systems. The technological challenge consists in rationally implementing 3D integration processes with hybrid materials (silicon, polymers, glass). The originality of our approach lies in the fact that we design innovative MEMS for application-oriented systems. Three main fields of research have been explored during this period:

"PyroMEMS and Nanoenergetics" — Nanostructured Energetic Materials (EM) are characterized by improved rate of energy release, stability, security (sensitivity to unwanted initiation). EMs therefore offer a very attractive source of onboard energy and power. In that context, LAAS explored the integration of nanoscale EMs into MEMS to provide high-energy-density source for heat and/or mechanical power. We have validated the off-chip energy requirements for both civil and military applications [Bre5] [Bre7] [Bre11].
During the 2005-2009 period, we focused our activity on 2 technological axis:

- *Development of new technological routes to integrate nEMs directly on electronic chips*

LAAS has already developed and published innovative technological process to integrate directly on a MEMS chip Al/CuO nanowired energetic layer. It is achieved by thermal oxidation of a thin evaporated copper layer at 450°C for 5 hours and by aluminium thermal evaporation inside the CuO nanowires (Fig. 2). A similar process has been proposed for Al/NiO and Al/MgO. We demonstrate an enhanced interfacial contact area between Al and oxide with no organic impurities, and our approach enables an easier integration into functional micro-systems[ACL333] [ACL414] [ACL417] [ACL473] [ACL515] [ACL551] [ACTI769] [ACTI831].

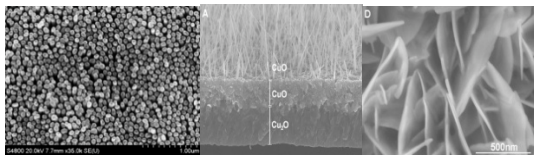

Figure 2: Nano energetic materials CuO/Al et NiO/Al.

- *Development of micro-energetic devices and explore their fields of applications*

We have chosen to illustrate our contribution through 2 micro devices:

- Integration of a microfluidic actuator (0.25mm²×100µm, overpressures>10kPa) into lab-on-chip/biochip for fluid ejection, which is based on the decomposition of a thin layer of energetic material deposited on a silicon microstructured platform (Fig. 3) [ACL391] [ACTI700].
- Integration of a MEMS Safe Arm and Fire device for safe miniature fuzing device. It integrates sensors, igniters, 2 nEMs for gas and heat generation, mechanical actuators, circuitry, power supply…) within 3cm^3. For the first time, it combines a mechanical arming unit with electrical safety functionalities on the same silicon initiator's chip and uses an energetic layer to generate 5 bar in a few mm^3 to dislock and move a screen that interrupts the explosive train. It requires only 635mW for ignition and actuation triggering (Fig. 3) [ACTI131] [ACTI412] [ACTI484].

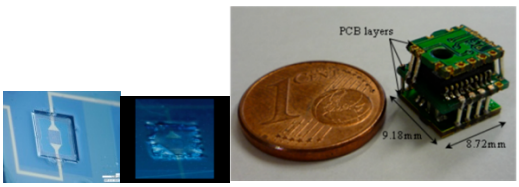

Figure 3: Micro pyrotechnical actuator for lab-on-a-chip and MEMS based arm and fire systems

"Development of a new sensor/actuator thermal device" — Our technology is based on conduction tunnel in a PN junction biased in reverse. The

technological process has been simplified (5 levels of photolithography) to obtain robust matrix sensors and actuators implementation (Fig. 4) [ACL124] [ACTI915] [ACTI1345] [ACTI1401] [ACTI1454].

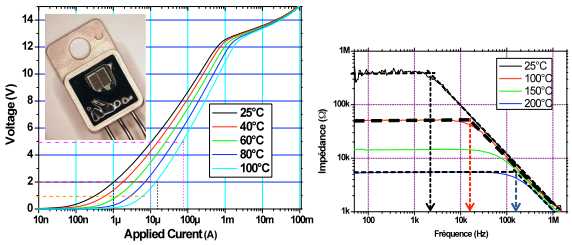

Figure 4: I (V) and Z (F) measurement temperature and mechanical deformation applied to the sensor

"**MEMS metrology"** — MEMS technology allows to have secondary voltage references with a wide range of voltage values (from a volts to a few hundreds of volts), which are very promising because of their expected performance (some parts in 10^7 of stability over a year). In a DC voltage reference, a feedback electronics to stabilize the mobile electrode at the pull-in point is necessary. For AC voltage reference, the actuation is ensured by an AC current which does not limit any more the mobile electrode displacement. MEMS based DC voltage references will be a response to a gap between the very expensive quantized Josephson voltage standards (10V upper limit value) and the affordable but noisy Zener diodes (10 V upper limit value). MEMS based AC voltage reference will constitute a real breakthrough for the AC voltage as no reference exists except that based on the Josephson effect, which is under development and will have the same limitation as in DC in terms of available values (max 10 V), practical implementation and cost, in addition to a very short bandwidth frequency (up to 10 kHz).
Since 2007, we have started collaboration with LNE (Laboratoire National de métrologie et d'Essai) to promote the concept of MEMS for metrology [ACL299] [ACL448] [ACL451] [ACL455] [ACTI1102] [ACTI1170].

This research axis lead us to build partnerships:

- *Inside the LAAS:*
  - polysilicon sensors for temperature and pressure intrahead. (M2D partnership),
  - embedded SiP application for power switches (ISGE partnership).
  - Feedback MEMS control (MRS partnership)
- *National level:*
  - ANR PYRACT, RTRA NACOMAT, DGA REI MICROAMORCE, PEPS avec Université de Nantes
- *International level:*
  - Switzerland: Université de Neuchatel
  - Taïwan University
  - Netherlands : European Space agency
- *Industry:*
  - LACROIX (INIMAT), SNECMA SPS, AIRBUS, ROXEL, NEXTER MUNITIONS, ESSILOR laboratoire commun Pix-cell

Micro-nano fluidics integration

Our research activity aims at developing micro/nanofluidic platforms dedicated to chemical and biological applications. The activity has targeted two major challenges:

- The multi functional integration for lab on chip applications or chemical process intensification.
- The exploration of nanoscale mechanisms in order to propose new functional concepts and to investigate the bioworld at the molecular scale.

Our applications are mostly focused on environment, separation science, diphasic flows and cellular biology.

"Multifunctional integration" — After a 5 years effort, we have developed robust processes for micro and nano channels fabrication in glass, silicon, and polymer materials [ACTI210]. Regarding polymeric systems, SU-8 was used as a structural material, and original methods to fabricate 3D microfluidic networks were proposed. We were the first to demonstrate surface micromachining of SU8 structural layers and to propose a lamination based fabrication method for the realization of 3D assemblies or multilevel microchanels network. In addition, using advanced MEMS technologies, we demonstrated the direct integration of microcoils in the polymeric matrix and obtained magneto-fluidic devices for magnetic particles sorting and manipulation [ACL365] [ACL115] [ACL162] [ACL201] [ACL301].

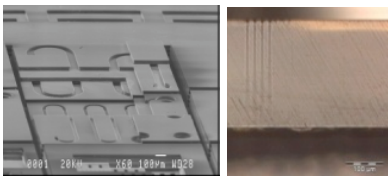

Figure 5: Su8 multilevel stacked fluidic pipes and traversing vias with high aspect ratio (500µm deep/∅10 µm)

Figure 6: Full polymer microfluidic system integrating microelectromagnets for magnetic sorting and trapping

Thermal actuators and sensors were also engineered and incorporated inside microchannels in order to monitor the local environment of biomolecules. This technology was combined to smart thermally responsive polymers (PNIPAM), and trapping/release

operations could be performed with proteins in aqueous environment [ACL223] [ACL365] [ACL201] [ACL400] [ACL418].

Silicon fluidic devices have found applications as miniaturiazed catalytic reactors, which showed great potential for removal of air pollutants such as **V**olatil **O**rganic **C**ompounds (acetone, toluene) [Bre14] [ACL429] [ACL166] [ACL384] [ACL608] [ACL681].

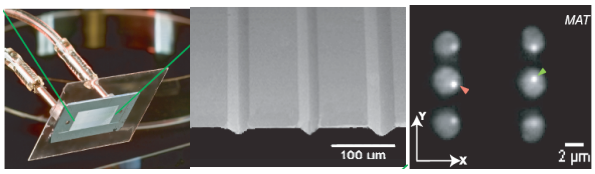

Figure 7: (Left) Ingrated Lab on Chip for 3D live cell imaging. (Middle) V-grooves for stereovision imaging. (Right) Two yeasts obsreved with their reflected images with our Lab-on-Chip

More recently, we devised Lab-on-Chip for high-throughput air droplets generation. These diphasic systems will be used to deflect light, and to implement new opto-fluidic systems. An original and patented fluidic device for 3D imaging in living cells was also integrated by combining silicon micro-machining and stereovision methods. This technology allows for the fastest 3D detection in small living specimens such as yeasts or bacteria (Fig.7) [ACL318] [ACL115] [ACL166] [ACL301] [ACL384].

"Nanofluidics" — Although microfluidics remains an active field of research involving a large corpus of researchers worldwide, the field of nanofluidics has been rapidly growing in the past 3 years. Given our experience in microfabrication, we decided to devise nanofluidic systems for life sciences applications and to gain insights on the nanoscale physics of fluid flows.

We have established processes to fabricate multi-scale devices with structural elements from the millimeter to the nanometer scale. Notably, we reached state-of-the-art precisions to produce 200-nm nano-channels over large fields, and our protocols are now exploited by other research groups of LAAS.

We intend to elucidate the molecular mechanism driving liquids inside nano-channels, which involve nano-scale physics at the liquid/glass interface. We also aim at fabricating new nanofluidic devices for life sciences applications, and in particular for the parallel manipulation of individual biomolecules (see prospective) [Bre6] [ACL115] [ACL166] [ACL301] [ACL384].

Our preliminary results show that nanoscale flows, which are driven by capillary forces, are fast ~1-100 µm/s. Their control in nanofluidic devices paves the way to diphasic mixing in still unexplored geometries, and to the development of new optical systems.

This research axis leads us to build partnership relations:

- *Inside the LAAS:*
  - Opto fluidic diphasic flow (PHOTO partnership),
  - Nanochannels and Nanowires (NBS partnership).
- *National level:*
  - ANR-PNano (Nanodrive, Nanobiosensor, Chromatomopinces), ACI-NMAC (Nanolab, Nanofluo) , ACI-Nanoscience (Samflu), ANR jeune chercheur Replichip, CNRS Prise de Risque (Replichip, 07/07) and (3D Cell, 03/09), Région (Thermofeel).
- *International level:*
  - Egide- MERLION (Univ. Singapour),
  - PRC-CNRS (Univ. NTU TAIWAN)
- *Industry:*
  - RHODIA, PIERRE FABRE

Systems for Structural and Human Health Monitoring

This research is focused on microsystems integration in new systems with the challenge of implementing a smart atmosphere based on the breakdown/ distribution of microsystems with autonomous communication, energy and decision. Our research efforts are focused on the design of nodes, or on the integration of systems built around MEMS that are either developed internally (see Advanced MEMS) or used as components on the shelves. In the latter case, it is necessary to prove and qualify the reliability of the microsystem in real conditions. Hence, we contribute to the development of a reliability physics, and we have been involved in the European projects PATENT on "MEMS and RELIABILITY", in POLYNOE, and we patented our developments with CNES [ACL168] [ACTI378] [ACTI552] [ACL23] [ACL168] [ACTI45].

Our system design methodology is based on a virtual prototyping approach in which we use multi-scale models developed in the group. We ultimately propose VHDL and/or VHDL AMS multi physics system models, which take into account the MEMS in its environment and its operating conditions, and we aim at predicting the reliability of the system before any manufacturing phase. Note that the CAD platform is extensively used, and we share our knowledge through VHDL and COMSOL models.

To clarify the scope of our field investigation on Wireless Sensor Networks, we have not been developing transceivers, we rather use a communication channel, and we integrate the algorithms of multi sensory fusion in order to

diagnose abnormal function. Finally, the issue of energy recovery is harvested based on mechanical and/or acoustic vibration, and we are working with specialists in storage and conversion. The embedded system applications, driven by the proximity of AESE and CancerBioSanté "Pôle d'excellence", are focused on industrial partnerships on the observation and diagnosis of health:

- **Health for people : "smart home systems" for the maintenance of elderly at home (**EDF, CEDOM, Hopital de Rangueil, maison de retraite de Tibiran-Jaunac THALES, EDF, CEDOM)
  - Sensor level: we have developed a new generation of presence detector based on bolometry for direct body temperature measurements. This approach is relevant for old people with slow displacements. It has been industrially protected with EDF [ACL23] [ACL493],

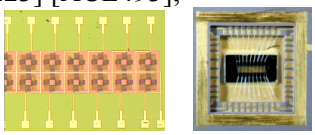

Figure 8: (a) Matrix thermopile sensor 2 × 8 (b) Micro-bonded sensor on support

  - Diagnosis level: we propose autoadaptative experimental models representing the users habits. The more complex algorithm has been developed for the PROSAFE project in the case of patients with Alzheimer disease [ACL428] [ACL10] [ACL23] [ACL428] [ACL443] [ACL493]
  - Experimentation level: we have implanted a complete system with a network connecting residents and doctors, and validated it with Toulouse-Muret Hospital, isolated housing (Orléans), and retirement pensions (Tibiran-Jaunac).

- **Health for structures: real time monitoring** of **structures for aeronautics** [wings (AIRBUS, EADS), blades (RATIER FIGEAC, LDL TECHNOLOGIES)] and buildings (EDF, TAGTECHNOLOGIES, SIEMENS, Labs: TIMC, ISAE)
  - We develop a new WSN based on motion sensors, and on accelerometer signal processing [Bre8][Bre9]. This technology has been transferred to a new company: TAG TECHNOLOGIES (created in 2006, 15 persons working today, 5 PhD students from LAAS).

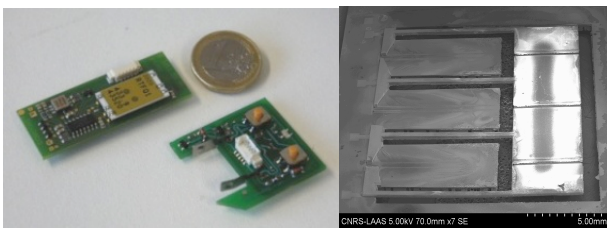

Figure 9: (a) Node motion sensor
(b) Power harvesting module design.

  - we develop a mechanical piezo harvesting node dedicated to the control of aeronautical structures (AIRBUS FRAE Autosens Project) [ACL125] [ACL338] [ACL294].

Significant projects and collaborations

Projects and collaboration have been described for each main strategic domain. Note that our average budget is around 700k€/year.

N2IS is involved in the joint laboratory Pix-Cell lab with ESSILOR International [Bre12][Bre13]. In that frame, we target the development of new concepts for optical devices applied to human vision. The long term objective is to replace the old ophthalmic glasses design based on successive deposition of thin films by a set of independent cells that encapsulate materials with new and active properties. In the field of optics, this technological option is unique, and open the way to the realization of optically customized glasses. This action will benefit from technological developments in N2IS especially on polymer technology applied to optics and micro fluidics as well as thermo mechanical modeling. A previous work has already led to the patenting of a method for transferring pixelized structures, and of generic designs of active lenses.
The following table summarizes our scientific output on different lines of research.

	Atomic Scale Modeling and Simulation	Advanced MEMS	Micro-nano fluidics integration	Systems for Structural and Human Health Monitoring
NE	3,5	4,3	4,8	5,3
Patents	0	4	2	5
Thesis	4	3	3	9
HdR	0	2	0	0
RiCL	22	24	11	11
CiCL	5	30	22	41
C. Ouvrage	0	0	1	1

We interact with the university and graduate school by helping to disseminate knowledge about our research topics:

- UPS: establishment of master « Ingénierie de la Matière: Modélisation des Procédés Physiques » (opened October 2008, 9 students)

- AIME training clean room : MEMS process development based on PN silicon diodes (6 schools & university)
- Ecole doctorale GEET: Microfluidics module.

Some of us are involved are involved in the program committees of conferences or GDR:
* EMRS Strasbourg 2004, MRS 2008 San Francisco, iMEMS2006, iMEMS2007
* International Workshop creation: “From molecule to drug design”, 2007, 2008, 2009.
* Management of GDR MicroNanoFluidique (GDR3158).

Microwaves and Opto-Microwaves for Telecomunications Systems – MOST –

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Long term visitors: A. Florea, H.L. Martinez-Reyes

Objectives and positioning

There is today an important need for highly integrated microwave systems based on microelectronics and nanoelectronics engineering and featuring a high level of complexity in order to fulfil the requirements of various applications fields, such as telecommunications, metrology, sensors or microwave imaging systems. However, in many applications, the complexity level is not the only important parameter of the system.
The carrier to noise ratio optimization is crucial, together with the system reliability. This is the case of **microwave and RF systems for space applications** for which integration, performance and reliability should be simultaneously achieved. Because our research group is located in Toulouse, our partnership with companies or agencies involved in the space and aeronautics market is strong and we are deeply involved in finding solutions to these problems. However, even in mass market, the circuit performance (particularly in terms of noise) can be the discriminating parameter between two competitive companies. In this application area, the need for an ever increasing complexity leads to system on chip (SoC) taking benefit of analog and digital modules, of programming capabilities which allow the circuit or the system to fit different needs. Our challenge is to design such circuits, taking simultaneously all these parameters into account and improving the quality of the RF signals.
However, in some cases, the classical MMIC circuit design approach is unable to reach the required level of performance. An important case is the one of resonators for which a high Q in a small volume can only be obtained taking benefit of different propagating waves: acoustic or optical. Microwave sources optimisation is one of the application field for which all these skills are required: phase noise modelling, microwave integrated circuit design and high Q resonators implementation. Two new approaches have been addressed in order to design low phase noise sources: micro-machined resonators and optical resonators or delay lines. The last case is quite complex, because it requires the modelling in a single system of electrical and optical devices.

Our investigations on these problems are focused on three main fields, which also corresponds to the internal structure of the MOST group:
1) Electrical noise: from single device to complex system
2) Advanced design and integration of microwave circuits and SoC
3) Generation and distribution of microwave and millimetre wave signals using optics
The association of such competences is original, and allows us a different approach for our investigations than the ones developed by the other research groups of either the microwave community, the noise community, or the optics community. We are clearly identified as a team of the microwave community, with an expertise in noise, in RF circuits and systems, and in optoelectronics.
Noise is of course the most transverse field in the group, and our knowledge of noise together with our skillness in circuit and systems design allows us to investigate on noise on a very large scale of applications, from the device to the system, and from the low frequencies to the millimetre wave range, and up to the optical domain. As an example, in the characterization field, we are probably among the few laboratories with noise measurement facilities for low frequency noise (1/f noise), high frequency noise parameters (up to 40 GHz), phase noise in frequency sources or devices (1 MHz – 40 GHz) and optoelectronic devices noise (laser amplitude and frequency noises).
Our modelling approaches also are original, with the ability to extract accurate device models including noise and nonlinearities, then to take benefit of these models in an accurate nonlinear description of a circuit, and finally to include this circuit in a system or in a SoC. These systems may involve analog or digital signals, or a large number of harmonic signals, or carriers of either microwave or optical type. To this purpose, we use commercial CAD platforms, but the modelling approach is indeed original in many cases and include in these platform some devices models which does not exist originally in the platform or involve a complexity level in circuit architecture which needs dedicated design approaches.

Highlights and Major Achievements

We will here describe the achievements for each of the three main research topics of MOST team. As explained in part I, these topics are not independent but strongly correlated, particularly at the interfaces (ex: noise in optical systems, low noise circuits…). However, the group organisation in three topics clarifies the scientific objectives and everyday management.

Electrical noise: from single device to complex system

This topic is decomposed in four main projects. The first one is related to the reliability and the robustness of electronic devices. The low-frequency noise (LFN) is used as a diagnostic tool to assess the quality of semiconductors. An original method combining electrical stress and LFN has been proposed to evaluate the reliability of Zener diodes [ACL365] and it was found very efficient for space applications where high-reliability is required. We also used LFN characterization and modelling to study the long-term reliability of silicon bipolar transistors subjected to low constraints during a very long period of use (15 years) in an industrial environment [ACL385]. The physical mechanisms responsible of the electrical ageing have been identified and localised by means of emission microscopy. Reverse base emitter stress and ESD stress have been also used to reproduce the electrical signatures of the ageing.

The second project concerns the noise properties of new devices. Several technologies of wide band gap HEMT based on AlGaN/GaN heterojunction and their impact on LFN characteristics have been investigated [ACTI932]. The presence of defects in the semiconductors and their impact on the carrier transport mechanisms has been identified and technological solutions to minimise these effects have been studied to improve the reliability [Ast08]. The noise properties (including low-frequency noise and millimetre noise) of metamorphic transistors (AlInAs/InGaAs/AlInAs grown on GaAs substrate) featuring nanometre gate length, have been studied in order to realise active cold loads for calibration of future radiometers [ACTI1468]. The impact of LFN on the long-term stability has been theoretically investigated and we have experimentally demonstrated that this technology is very attractive to reach the different goals in terms of stability and noise temperature in the millimetre wave range.

The third project is related to the noise of microwave devices operating under nonlinear conditions (oscillators and amplifiers). Upconversion of LFN in GaInP/GaAs [ACL199] and SiGe [ACTI925] heterojunction bipolar transistors has been studied in order to improve phase noise modelling of high spectral purity microwave sources. The most complex models proposed are based on a nonlinear noise sources approach (cyclostationary noise). An SiGe HBT based X band amplifier has been designed, featuring a phase noise of -163 dBc/Hz at 10 kHz offset [ACLN51].

The noise behaviour of microwave amplifiers operating under nonlinear conditions has been theoretically (using a behavioural model) and experimentally investigated [ACL116]. We also demonstrated the possibility to measure the four microwave noise parameters of active devices (amplifiers and transistors) in the presence of an interferer [ACL294]. This can be used to design new architectures of robust receiving systems which can be seriously impacted by the multiplicity of communication signals.

Finally, the phase noise in FBAR resonators [ACL236] has been experimentally investigated and we found that its influence must be taken into account in the overall noise performance of an oscillator stabilised on such a resonator. FBAR resonators are indeed subject to a natural 1/f fluctuation of their resonant frequency. This study has been followed by experimental investigations on the nonlinear behaviour of SMR piezoelectric resonators [ACTI1083].

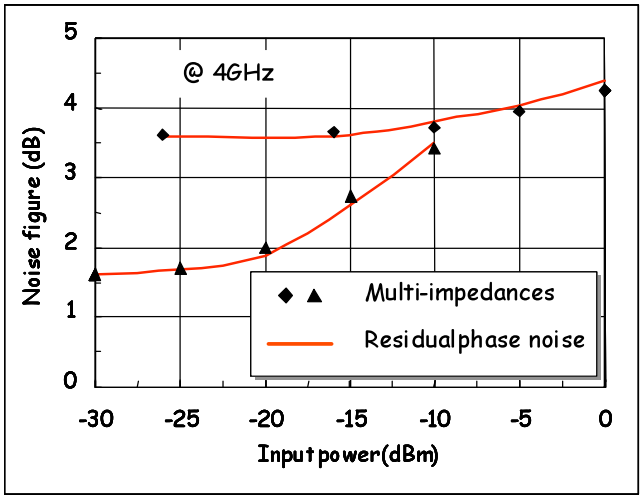

Figure 1: Noise figure of amplifiers operating under nonlinear conditions measured from different techniques

The last project concerns the noise in complex systems. Sampling phase detectors (SPD) are very effective in phase locking of low phase noise microwave oscillators but its noise level must be reduced to fit future requirements of complex modulation schemes. The role of the different active devices (step recovery diode, transistors and mixer diodes) on noise generation in SPD has been studied by means of nonlinear simulations and LFN measurements. It was found that most of the different elements can impact the overall SPD noise, depending on the baseband frequency, but that the

excess noise of mixer diodes must be specifically considered [ACTN335].
The influence of noise and parasitic signals on the wireless radiofrequency link in an embedded system (tire pressure monitoring) for automotive applications has recently been adressed. The contribution of the different elements (rim, tire and ground) to the radio-link budget, which is a keystone of the overall system reliability, has been investigated using advanced simulations and near field measurement technique [ACTN329].

Advanced design and integration of microwave circuits and SoC

The purpose of this topic is to help at the design and integration of high performance circuits and systems by acting at different levels: materials, components, and topologies [ACL258].
In the two first levels, material and component, the main goal is to optimise available components of standard technologies by above-IC post-processing. Firstly, the use of a thin layer of ferromagnetic material over standard inductors has shown a great improvement of the inductance value through a permeability increase [ACTI973]. Related to this study, a direct characterisation method to measure *thin* layers *relative* permeability has been set up, because *massive* layer measurements shows wrong permeability resonance value, and classical *thin* layer measurements give the *effective* permeability instead of the *relative* one.
In a second work, an above-IC post-processing has been developed to optimise power RF LDMOS, allowing the integration of power inductors grown over a thick Su8 layer. The choice of the dielectric material has also led us to develop a new characterisation method for the permittivity of such dielectric. These new power inductors show a high quality factor (55 at 6 GHz for a 0.7 nH inductor).
In the third level, circuit and system, we have developed original concepts able to raise available technologies at their highest performance: many designs have shown state-of-the-art performances. All designs share the same purpose: to be used in the transceiver part of embedded systems (reduced consumption, reduced cost, reconfigurability, ...). For example, on the receiver side, a low-cost and low-power RF receiver for 2.4GHz IEEE 802.15.4 WPAN standard has been integrated in a 90-nm CMOS technology, with an area saving of 90 % and a consumption lowered at 50 % compared to equivalent circuits [ACTI1056, ACL449]. On the emitter side, a high-efficiency high-linearity monolithic RF power amplifier has been integrated: its efficiency has been increased by lowering the current consumption in the linearizer at low output power [ACTI147, ACTI1168]. We also started to design millimeter wave functions on BiCMOS technology: a mixer in BiCMOS 0.13 µm has been developed and is very promising through mixed electrical/electromagnetical simulations [ACTI1502]. Original topologies of programmable active attenuator and phase shifter are also investigated for integration in new architectures of avionics radar transceivers.
A large number of designs have been done also in the area of frequency synthesis. Before 2005, we worked on digitalizing all the functions of a phase-locked loop. Since then we have considered two other ways:
An analog way, with the use of a new kind of integrated resonators (BAW) for high purity frequency references: two state-of-the-art ultra-low phase noise 5 GHz BAW-based oscillators were designed [ACTI357, ACTI440].
An all-digital way, with a state-of-the-art direct digital frequency synthesis (DDS), for the first time on SiGe above the gigahertz (6 GHz clock frequency) and with a very low consumption (360 mW) compared to the few watts (!) of existing realizations [ACL396]. Moreover, we discovered that in some specific situations, the DDS can be used as an UWB pulse generator (Patent 0856778, deposited in 2008).

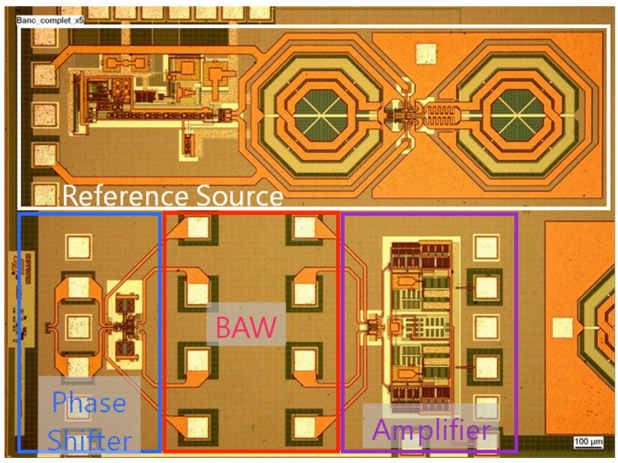

Figure 2: Integrated phase noise test bench near 2 GHz, using BAW resonators

Finally, we have also started in 2005 an activity on integrated test bench design, to take advantage of our long time measurement background in the MOST group on one hand, and our prolific design activity on the other. We began with a BAW-based integrated phase noise test bench: we showed that the design of such a bench was feasible in a BiCMOS technology, and was very interesting on many aspects: simplifying measurement procedure, doing it fast, avoiding use of probe station and many expensive external 50 Ω devices [ACTI1419, ACTI1420, and patent 0757729, deposited in 2007].

Generation and distribution of microwave and millimetre wave signals using optics

This topic has started in september 2001. The two first thesis were mainly dedicated to the problem of the distribution of frequency reference signals with fiber optics in a satellite (joint work with Thales Alenia Space). The second thesis ended in October 2006, and was focused on low phase noise microwave optical links, with application to clock distribution and also to metrological systems [ACL329, ACTI220]. Low phase noise links at 10 GHz and 16 GHz have been designed, based on original modulation techniques on the emitter side (carrier rejection with feedback bias control) and optically injection locked oscillators on the receiver side [ACTI575, ACTI428]. This technology is today planned for a real implementation in the satellite.

However, optics can do much better than a simple distribution of microwave signals. It is possible to take benefit of the extremely high Q factor of some optical devices to stabilize microwave sources, with a performance in terms of Q factor much higher than its microwave competitors. Therefore, because of our experience in microwave oscillators design and in low phase noise optical links, we have started to investigate on low phase noise microwave generation using optics.

The preliminary work in 2005 and 2006 was dedicated to set up a characterization bench for high Q whispering gallery modes optical resonators, such as silica spheres or monocristaline polished disks (CaF_2, quartz…), featuring optical Q factors in excess of 10^9. It is the frequency difference between two modes of these resonators which is used to stabilize the microwave system. The resonators coupling has been the first problem to solve (nanometric control of the distance), then we had to deal with the difficulty of inducing light in these resonators: the Q factor is so high that the laser linewidth is often larger than the resonator bandwidth, and that any amount of power induced creates a shift of the resonant frequency because of self heating. Once this last problem had been solved, thanks to appropriate feedback techniques on the laser, an extensive study of these resonators has started [ACTI1307, ACTI1348].

An original resonator approach has been proposed, based on a resonant fiber loop [ACL535] and featuring a Q factor of $3\ 10^9$ (20 m loop). Compared to the old delay line technique, the resonator approach increases the Q factor with a ratio in performance which may be as high as 50 (a 20 m resonant loop is the equivalent of a 1 km delay line). Such a resonator is of 2D geometry, and can thus be easily included in a system. A patent has also been proposed on a special version of this resonator (no information may be given at this time). Finally, a 10 GHz oscillator based on this resonator has been realized [ACTI1450]. It is the first oscillator of this type ever published.

However, in spite of its high Q factor, this oscillator is relatively noisy. Therefore, a modelling approach has been set up able to describe the noise conversion in a microwave optical system. This approach uses the microwave CAD software Agilent ADS, and electrical or mathematical equivalent devices have been implemented on this software [ACTI1097]. The interest of this approach relies in its ability to take into account the nonlinear noise conversions between DC, RF and optical carriers, thanks to the harmonic balance technique. It has been used to optimise a microwave frequency discriminator based on an optical delay line, which features today state of the art performance (L(f) < -151 dBc/Hz at 10 kHz offset).

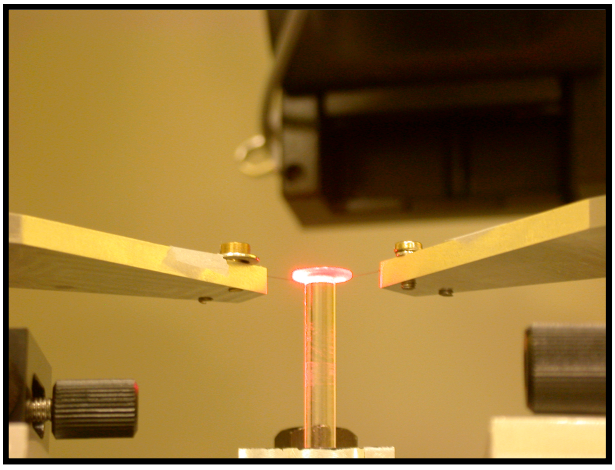

Figure 3: measurement of an optical WGM resonator made of a polished quartz disk ($Q = 4\ 10^9$)

Significant projects and collaborations

Most of the works described here have been performed in the frame of different projects and contracts involving other teams and/or industry partners. A brief description of these projects is listed below, starting with European project and ending with regional collaborations or industrially oriented thesis.

European projects

MARTINA and MOBILIS have been two of the most important projects of this period for our group. The goal of these two STREP projects was to design various circuits based on micromachined BAW resonators, and also to perform fundamental studies on these resonators (nonlinearity, noise…). They have involved a large number of partners of different European countries, three other CNRS laboratories (XLIM Limoges, IMS Bordeaux, IEMN Lille), CEA-LETI and ST Grenoble in France. MOBILIS is ending in June 2009.

ARAMOS is an EDA project focused on frequency generation using optics, which involves four different laboratories of Thales near Paris (and leaded by TRT), IEMN Lille, LPL Rennes and two Italian teams of SELEX (Roma) and CNR-IFAC (Florence). ARAMOS will end in January 2011.
The ESA project "Active calibration for radiometers", with EADS-Astrium Toulouse, has been achieved in 2009, and is followed by a project funded by the Midi Pyrénées Regional Council.

National projects

ANDRO was an ANR project focused on GaN FET dedicated to power and low noise applications, in which our involvement on devices characterization, modelling and even hybrid circuit design has been important. This project has involved the consortium TIGER (Thales and IEMN). Another ANR project on GaN power devices, MOREGAN, is still going on and involves a collaboration between several partners among which CHREA Sophia-Antipolis and LAAS are in charge of the technological parts, characterization and modelling.
VELO is an ANR project focused on the design of millimetre wave circuits for the application to the automotive radar. The goal is to design an integrated impulse 79 GHz ultrawideband radar. Our work on the receiver of this radar is performed in collaboration with ST Microelectronics, IMS Bordeaux, LABSTIC Brest, the CEA-LETI and the MINC group at LAAS.
FINEST is a project of the FRAE (Fondation Recherche Aéronautique Espace), focused on balanced integrated functions in the millimetre wave range. It is a joint work with ENSEA Paris and XLIM Limoges.
FAST is starting in 2009, and is a FUI project dedicated to the communications (internet) between a plane and a satellite, and involving various partners: ENSTB Brest, ENAC Toulouse, AXESS Europe Toulouse... Our contribution is focused on the design of innovative integrated circuits.
The ANR project O2E, with FEMTO-ST Besançon and ENSSAT Lannion has been focused on the development of microwave optical oscillators, either based on resonators or delay lines. It has ended in feb. 2009, and it was partly in parallel with a CNES program on this topic, which will end at the end of 2009 with practical realisations.

Regional projects

Various projects have involved Toulouse space industry and the CNES (National Centre for Space Studies), and received generally a complement in financing of the Midi Pyrénées Regional Council.
This is the case of a study with Thales Alenia Space focused on the reliability of a complex PLL system used for frequency synthesis in the satellite (still going on). This is the case also of two successive projects on the use of optical fiber in satellite for reference frequency distribution, with Thales Alenia Space.
Freescale Semiconductor Toulouse is also working with our team, to improve its power amplifier with new approaches for high Q inductors.
Another project is in relation with the local automotive industry i.e. Continental Automotive, such as the characterization and modelling of the radiolink budget (signal over noise) of a Tire Pressure Monitoring System between the pressure sensors embedded in each wheel units and the onboard computer (partly funded by the regional council).
Finally, our relations with local chemistry teams in Toulouse (LCC CNRS and University) as leaded to a PPF project of higher education and research ministry. This project is dedicated to ferromagnetic materials and their applications to microwave circuits.

International relations

Apart for the teams involved in the above mentioned european projects, we are maintaining close relations with at least two other foreign teams : one in Berlin (Germany) involved in circuit design and device modelling (FBH – Ferdinand Braun Institute), and another one in Ensenada (Mexico) involved in device modelling, and also optical control of microwave devices. Joint work has been performed thanks to exchanges of researchers (on short or long period).

Science diffusion and education

All MOST permanent researchers are deeply involved in education, at different levels (from DUT to Master), and in different university decisional councils: scientific council, administrative council, teaching department… Additionally one MOST member is actually one of the P. Sabatier University Vice-Chairman in charge of European affairs and another one is the Chairman of the electrical engineering doctoral school of Toulouse (GEET: 300 PhD's in progress).
Also, two important conferences have been organised in Toulouse by our group: the Journées Nationales Micro-ondes 2007, with 620 attendees, and the 2009 NEWCAS-TESA Conference, with 160 attendees.
Finally, the experience acquired by our PhD students during their thesis is well recognised by our industry partners, and all our former PhD students of these last four years are today working either in space industry (Thales Alenia Space, Callisto Space and CNES) or in electronics industry (Freescale, Axess Europe, ST Microelectronics).

Microdevices and Microsystems of Detection – M2D –

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Long term visitors: A. Canals, S. Brida, L. Rabbia, W. Sant, C.H. Shim, S. Vinsonneau

Objectives and positioning

Microsystems development requires the heterogeneous integration of elementary functions related to multidisciplinary domains: electrical, mechanical, optical, physical, chemical, biological… The realisation of such functions formulates new technological problems. Indeed, contrary to devices for data treatment whose design and fabrication use microelectronics traditional know-how, the microsystems main active elements, i.e. sensors, transducers and actuators, require the development of specific technologies. This leads, on the one hand, to use non-standard processes as well as to integrate new materials originally non-compatible with silicon technology and, on the other hand, to develop specific technological platforms, focusing on mass fabrication, reproducibility and reliability.

Thus, upstream to the microsystems design and realisation, a research field exists that involves studies concerning materials integration processes as well as their properties of interest. Furthermore, materials and their functional properties have to be considered according to a given application and therefore to a specific microdevice. This microdevice becomes finally the best test-vehicle for studying materials and processes integration according to the chosen functionality. Thus, through the development of dedicated technological platforms, the microsystems realisation is finally demonstrated according to the application of interest.

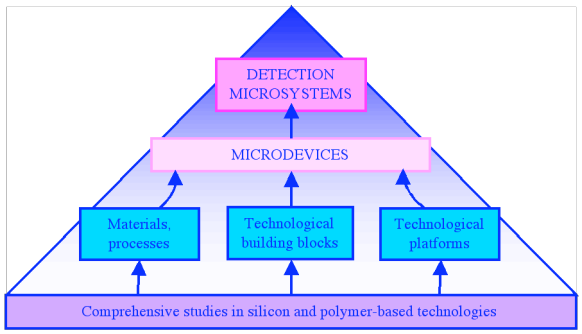

Figure 1: Frame of the M2D research activities

The M2D group activities occur in the frame of this upstream research field. Considering mainly silicon-based and polymer-based technologies, they concern more precisely the study of integration processes and integrated material properties, as well as the development of specific microdevices, and are finally focused on the realisation of detection microsystems (figure 1).

In term of silicon and polymer-based technological research, the M2D group approach aims to define theoretical and/or semi-empirical relations between integrated materials properties and integration process technological parameters. Accordingly, studies emphasize theory, modelling, simulation, characterization and/or use of specific microdevices. They plan to understand the main process mechanisms in order to optimize the integrated materials properties for specific applications.

In term of detection microsystems, the approach is focused on technological integration (figure 2). Starting from upstream collaborations with different scientific fields as materials and processes sciences, mechanics, optics, physics, chemistry, biology,…, the M2D group research activities concern the design, the realisation, the characterisation and the optimisation of microdevice platforms and finally of mass-fabricated detection microsystems in order to realise pre-series and to perform industrial transfer.

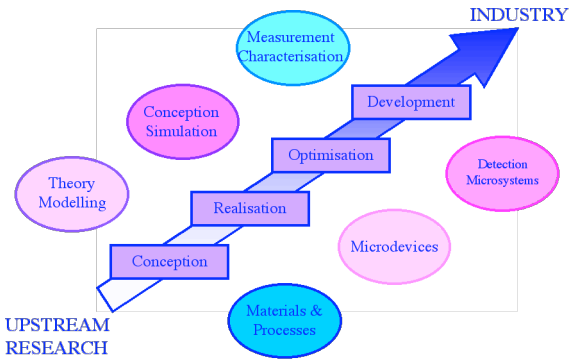

Figure 2: Detection microsystems research strategy

Highlights and Major Achievements

The research topics of the M2D group are of course restricted. The "state of the art" analysis, our skills, know-how and equipments, as well as the LAAS

scientific strategy have guided our choices. Thus the following studies have been carried on or undertaken.

CVD processes

During the 2005-2009 period, our research works on low-pressure chemical vapour deposition (LPCVD) processes have been focused on two main topics.
First, we have investigated the performance of the CVD process of boron doped silicon films to enter in the elaboration of integrated 3D capacitors (ISGE group collaboration). The key point was the conformity of the deposited Si:B layers in trenches with a very high aspect ratio (1:50 typically). Our works have not only shown that the layers are perfectly conformal, but also that stress optimisation enables the complete filling of the trenches, giving a perfect wafer planarisation. In addition, we have shown that, in spite of the high thickness required by planarisation (3-7µm), the wafers are supporting further processes at high temperature (diffusion of boron at 1050°C for instance). All these studies allow the development of a unique fabrication process for 3D capacitors, and offer numerous microfabrication solutions for other 3D microdevices.
In parallel, research woks have dealt with the deposition of thin insulating silicon oxynitride SiO_xN_y layers for micro-electro-mechanical-systems (MEMS) applications. The problem was to find reliable CVD processes that give low stress, i.e between 0 and +100 MPa, after annealing. The SiO_xN_y layers various properties, i.e. deposition rate, refractive index, residual stress, dielectric constant, stoichiometry, as well as hydrogen content in the case of plasma-enhanced CVD processes (PECVD), have been thoroughly studied. Thus, a low-stress silicon oxynitride deposition process has been defined and thin-membrane-based test microdevices have been successfully fabricated. Presently, this SiO_xN_y technological platform is running for the realisation of MEMS-based microsensors.

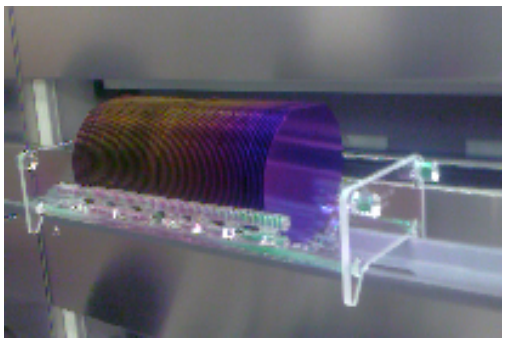

Figure 3: LPCVD deposition of SiO_xN_y films

Ultra-shallow source/drain junctions: new materials and processes

The aim of this research activity is to understand and model the physical phenomena related to the fabrication process of silicon-based ultra-shallow junctions (USJs) for future MOS transistors. In addition with the conventional "implantation-anneal" procedure, new technological solutions are constantly proposed to fulfil the ITRS requirements. The major problems of these techniques are related to their non-equilibrium character. Indeed, during the activation anneals, all species in excess tend to precipitate into various types of extended defects, which are responsible for dopant diffusion and activation anomalies. Finally, our researches have also concerned new materials expected to improve transistors performances, such as silicon on insulator (SOI) substrates and Ge-based materials.
In addition to the characterisation of defects in silicon, our research was extensively focused on their impact on dopant diffusion and activation. We measured and modelled the trapping of boron atoms by defects during annealing. For highly doped P-type silicon, we showed that the boron-induced clusters (BICs) induce Hall scattering factor and mobility variations. We explained the boron deactivation/ reactivation in amorphised USJs during annealing in terms of the concomital dissolution of amorphisation defects and BICs. Finally, we showed how to control these anomalies by F^+ or C^+ co-implants.
We also studied the formation of USJs in SOI substrates. We quantified the recombination length of the buried Si/SiO_2 interface, responsible for a reduced formation of extended defects and a reduction of boron enhanced diffusion. Despite these advantages, we found that even for very thin SOI (<20 nm), defects formation is not completely inhibited, in agreement with the measured degradation of electron and hole mobility in thin SOI and sSOI structures. We therefore investigated alternative "vacancy engineering"-based methods to reduce the interstitial population in SOI materials.
Finally, we also investigated germanium-based materials, due to their ability to increase the carrier mobility. A possible approach consists in the fabrication of strained SiGe source/drain regions by selectively depositing a germanium layer on a silicon substrate followed by thermal Ge–Si interdiffusion, therefore inducing uniaxial stress in the channel. To this purpose, we first developed a new MCs_2^+ SIMS method for the accurate quantification of germanium in SiGe alloys. We then applied this method to the investigation of Ge–Si interdiffusion and showed that although being mostly assisted by a vacancy mechanism, it exhibits a non-negligible interstitial contribution ($f_I \sim 0.17$ at 900°C).

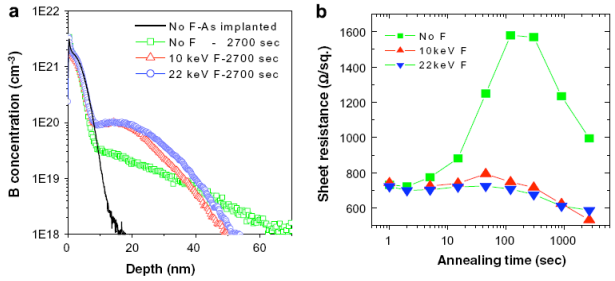

Figure 4: SIMS profiles (a) and sheet resistance values (b) of 0.5keV-1e15cm^{-2} boron implant samples, before (solid) and after (squares) a 2700s-800°C RTA, without or with 10 or 22keV F^+ co-implants (green, red and blue curves)

This work is the result of a durable collaboration (>15 years) between LAAS and CEMES, all based in Toulouse. The skills developed by our team and the quality of our results contributed to establish the state of the art in the domain of USJ fabrication.

Photo-emission properties of silicon nanocrystals

The CMOS monolithic integration of photonic components is one of the main challenges of the next decade. In this context, the demonstration of photo-emission from silicon nanocrystals (Si-nc) has opened new research opportunities for the development of a silicon-based integrated optics. With the mobility of E. Bedel-Pereira, the M2D group has focused its activities towards this research topic. Works deal with the structural, optical and electrical properties of Si-nc produced from LPCVD SiO_x films. The influence of layer thickness, Si content and annealing conditions was analysed in detail. In order to control and optimize the Si-nc growth, we have introduced an original step which consists in a two-step anneal, i.e. a rapid annealing followed by a standard one, to separate the Si-nc germination and growth phases. Efficient 300K light emitting Si-nc of different sizes (average diameter: 3-5 nm) have been fabricated. The emission shows a wide band in the range 750-900nm. Fabrication conditions have been optimized and we have obtained a photoluminescence efficiency of 0.02-0.2%, depending on excitation wavelength (figure 5). Furthermore, a systematic study of emission properties between 12 and 300K has allowed us to gain more insight on the light emission origin.

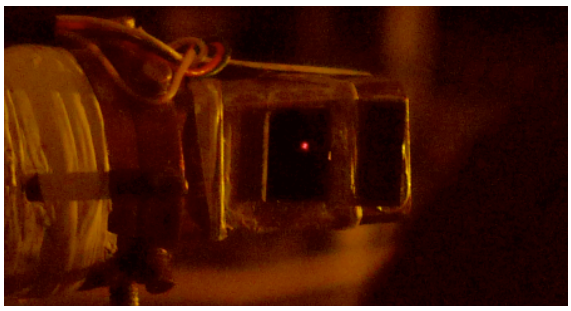

Figure 5: Red-light photoluminescence from silicon nanocrystals under laser excitation

Microlithographic processes

With the creation of the PIXCEL joint laboratory with ESSILOR company, a new technological challenge was to innovate ophthalmic glasses by realising patterns of independent pixels, filled with optically active liquids and finally sealed (figure 6-a). Thus, the curvature variation is replaced by the refractive index one. To realise this new generation of digital ophthalmic glasses, microlithographic processes have been studied. The surface microstructuration has been developed with SU8 resin photolithography techniques (figure 6-b). The main parameters (geometry, dimensions, aspect ratio and filling ratio) have been then optimised. Thus, a one-micron resolution has been reached and improved microstructures (200-micron wide, 5 or 20-micron thick, filling ratio: 99%) have been realised. The second step consists in filling the microtanks pattern by liquid with optical properties. For this purpose, the chosen technology has been inkjet techniques for its good printing quality and microdispensing accuracy. Experiments describing the influence of inkjet technological parameters on the droplet velocity and ejection stability have been realized. The obtained results have permitted to develop a relation between droplet velocity and the main printing parameters. Thus, by adjusting the driving voltage according to temperature, the droplet velocity is stabilized and the print quality is optimized. Finally, studies on packaging techniques in order to set up mass fabrication processes for the patterns sealing have also been developed.

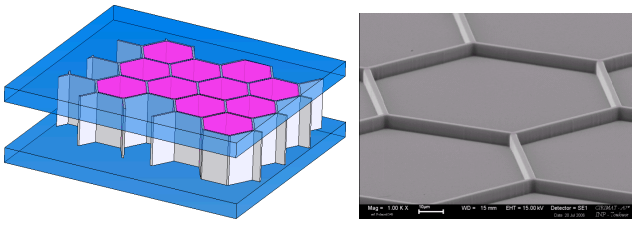

Figure 6: a) Picture of digital surface glasses
b) MEB image of SU8-based surface patterning

Radiation microsensors

Lastly, the activity about radiation sensors has concerned ionizing radiation and neutron dosimetry as well as readout circuitry for particle detectors.
Research activities have concerned three main projects. First, in collaboration with TRAD company and Claudius Regaud Institute, a study has been started about the design and development of a radiation sensors (figure 7) for in-vivo measurement during a radiotherapy treatment. The results obtained are very encouraging and a patent has been submitted for a system with enhanced capability. Second, a study is in progress in collaboration with Aristotle University of Thessaloniki (AUTH) about the design

and integration of a low-power, low-noise, ASIC front-end readout circuit for a particle detector. An original current-mode circuit has been designed and a patent has been submitted. It emphasizes a charge preamplifier whose noise level is independent of the detector capacitance, allowing low noise and large area detectors. Third, a study is in progress with AUTH about the realisation of a neutron dosimeter using a MOS transistor and a (n,α) converter. Two series of tests involving two different conversion materials have led to very encouraging results (sensitivity to thermal neutrons: 11 V/Sv).

Concerning development actions, MOS dosimeters from LAAS have been selected by CERN to be used at the LHC in the RADMON dosimetry monitors. Two batches of microsensors have been fabricated, characterized and provided to CERN. Then, in collaboration with the "Instituto Nacional de Tecnologia Aerospacial" (INTA - Spain), we worked on the development of the OPTOS System to be launched 2009: we had to provide the MOS dosimeters, to assist INTA in the design of the measurement platform, and to participate to the setting up of an INTA team specialised for MOS radiation dosimetry in space. We have also studied and provided to ONERA 4" micrometeoroids detectors for the SODAD module to be launched by CNES. A second batch of MOS dosimeters has been fabricated and provided to EDF. These sensors are part of an autonomous dosimetric system installed in nuclear plants. Finally, we have provided SEREPS company with a batch of MOS dosimeters for high dose measurements.

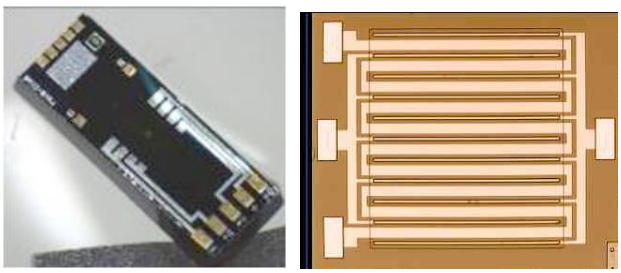

Figure 7: PS-MEMS pressure sensor (left) and MOS radiation sensor (right)

Pressure/stress microsensors

Concerning pressure microsensors, studies are focused on the development of micro-electro-mechanical systems (MEMS) based on capacitive, piezoresistive or electromagnetic transductions according to three main projects.

The first project is about intracranial or intravascular pressure measurement. Its aim is to develop a miniaturized, telemetric and in-situ self-calibrated microsensor for medical diagnosis (figure 7). Our activities are focused on the development (design, fabrication, test) of the sensing cell. Prototypes fabricated using wafer integration of silicon and SOI wafers involve pressure and temperature sensors as well as integrated electrostatic pressure generator. In parallel, LAAS participates to the sensors integration into specific catheter. Now all the parts of the sensor are ready and the final integration will start soon for in vitro and in vivo tests.

The second project is about collective packaging for aeronautic pressure sensor (AUXITROL company collaboration). The objective of this study is to simplify the classical packaging by using collective techniques and by removing oil and metallic membrane. The main idea was to change the sensor packaging configuration using a cap for the protection of sensitive part and by applying directly the pressure on the back side of silicon membrane. Three different solutions of collective packaging have been investigated: Pyrex cap with anodic bonding on silicon, silicon cap with Au/Si eutectic and with direct Si/Si bonding. The first one has been validated and will be transferred soon. The second one is still under optimisation and the third one has been launched few months ago.

The third project is about new transduction principle using radiofrequency (RF) electrical function in order to provide powerless sensors. This new researches started in February 2005, in collaboration with the MINC group. Now these studies are focused on autonomous wireless sensors network (SACER project). The first demonstrator is about a pressure sensor where a silicon-based membrane modifies the resonant frequency of RF resonator. This demonstrator has been designed, fabricated and characterized with on wafer procedure using a specific RF tests bench. The working principle of this new transduction principle has been validated, showing very high sensitivity (a 1Ghz shift for a 1µm displacement). The integration of antenna is now under progress for RADAR interrogation.

Gas microsensors

The gas sensor activities are currently focused on the development of semi-conducting microsensors, with moderate cost and low consumption in order to develop an integrated electronic nose for different applications as environment, transport, home automation, agro-industry and/or still defence. Their realization leans on the development of new technological processes (new materials, new structures, new designs and multisensor platforms), integration of different sensing materials (metal oxides), multiphysical simulations, electric and thermal characterizations and finally on the signal processing with dedicated electronic circuits. Since 2005, most important developments have been focused on stable microhotplates for high operating temperatures (around 600°C) (figure 8) and on gas-surface modelling to understand kinetic chemical

reactions between target gases and the sensing layer. In this frame, the LAAS project APROCH-CO_2 was to define theoretical bases useful for understanding the kinetic reactions between the SnO_2 surface and the CO_2 gas, so difficult to detect by conductimetry. Concerning technology developments, the "Integrated Electronic Nose" project, in collaboration with IM2NP and EMSE-SPIN, has allowed the realisation of new generic four-sensors platforms with integration of SnO_2 and WO_3 thin films as sensing materials. First experimental results were very promising since they showed the feasibility of detecting few ppm of CO, NO_2, ethanol and very low concentrations of ozone (few ppb). Recent collaboration with ALPHA-MOS company will permit the achievement of new gas detectors based on multisensor platforms for food industry.

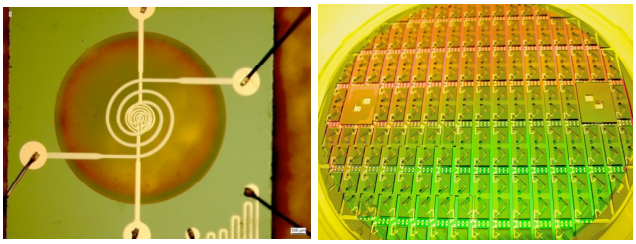

Figure 8: MEMS gas microsensor (left) and pH-ChemFET micro-analysis systems (right)

Liquid phase electrochemical microsensors

In the frame of chemical microsensors, research activities are involved in the integration of electrochemical transduction principles using silicon and polymer technologies. They have concerned the set up of technological platforms respectively dedicated to chemical field effect transistors (ChemFET) and electrochemical microcells (ElecCell), the study of the potentiometric and amperometric electrochemical transduction, the integration of (bio)chemical-sensitive layers, the development of packaging techniques (from wafer to system level) for the liquid phase measurement and/or the fluid handling, the realisation of data treatment interfaces, as well as the modelling of bio-electrochemical detection principles.

Since 2005, the developments of liquid phase chemical microsensors have been oriented towards health applications. Concerning the ChemFET platform, researches have been focused on the integration of pH-metry techniques for medical analyses. Two leading applications have driven these researches. The first one concerns the development and the industrial transfer of enzymatic field effect transistors EnFETs for the urea and creatinin detection in the frame of the haemodialysis domain (collaboration HEMODIA/CAPTOMED company). The second application concerns the monitoring of bacterial activities in microvolume (≈ 1 mm^3) for medical analysis applications (figure 9) in collaboration with the ELITECH company. Concerning the ElecCell platform, the researches are currently driven by a project concerning the detection of anti-oxidant species (acid ascorbic, acid uric, glutathion) for the skin analysis and cosmetic applications in collaboration with the LGC laboratory and the "Pierre Fabre Dermocosmétique" company.

Significant projects and collaborations

- LAAS project TEOS (2006-2008)
- European Projects NanoCMOS (2003-2005), PullNANO (2006-2008) and ATOMICS (2006-2009) in collaboration CEA-LETI, ST-Microelectronics, SOITEC, IEMN-CNRS, University of Surrey, University of Newcastle, Fraunhofer Institute Erlangen, IMEL Athens and Mattson Thermal Products Dornstad
- research contracts "Nano2008" (2003-2007) and "Nano2012" (2008-2011) with ST-Microelectronics
- joint laboratory PIXCEL with ESSILOR (2006-2009)
- ANR-TECSAN project CAPTAM (2006-2009) in collaboration with INSERM, CHU Purpan, EPSILON Engineering and HEMODIA
- research contract with AUXITROL (2006-2009)
- DGE project SACER in collaboration with a pool of SMEs, AIRBUS and INTESPACE (2007-2011)
- Midi-Pyrénées regional project and related research contract (2008-2010) in collaboration with TRAD and ICR
- research contract with TRAD and AUTH Thessaloniki (2007-2009).
- research contracts with ONERA (2006-2009), EADS (2007-2009), INTA Madrid (2008-2009)
- ANR-Blanc project MOBIDIC (2007-2010) in collaboration with ISGE group, LEG, LMP and CIME-Nanotech
- European project GRD5 – Nanosensoflex (2002-2005) in collaboration with CNRS-LCC (F), University of Hull (UK), University of Saarland (G), FIAT Research Center (I), NANOSENSE (F), Microchemical Systems (CH), ESSER (G), SAIA-BURGESS (G).
- National Project (ACI-CNRS 2004-2006) in collaboration with IM2NP (Marseille) and the EMSE-SPIN (St-Etienne)
- Research contract with ALPHA MOS (2009-2011)
- LAAS project APROCH-CO_2 (2006-2008)
- research contract MICROMEDIA with HEMODIA (2005-2008)
- ITAV project NUTRIPUCE in collaboration with INSERM, UPS and PHYSIOGENEX (2006-2008)
- research contract with ELITECH (2007-2009)
- Midi-Pyrénées regional project and related research contracts (2007-2010) in collaboration with LGC-UPS and PIERRE FABRE DERMOCOSMETICS

NanoBioSystems – NBS –

Permanent Staff:
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Non Permanent Staff:
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PhD students: T. Alava, A. Cerf, S. Guillon, S. Habtoun, A. Labernadie, L. Le Doan Than, S. Salomon, F. Seichepine, C. Tinguely
Long term visitors: A. Martinez, C. Séverac

Objectives and positioning

Our research group has been founded in May 2002 as the "Nanoaddressing, Nanobiotechnology" group. Only one year later, Nanobiotechnology is "officially" defined as a discipline at the crossroads between life sciences and nanotechnology (Nature Biotech., vol.21 n°10, 2003). At that time, *Isi web of science* gathers 28 publications written by people belonging to "Nanobio"-spelling research entities (to be compared with more than 1900 hits that the same web engine would display today). In addition, one should note that during the 2000-2009 period of time partially *nanobiotech*-oriented scientific journal (with sky-rocketing impact factors) are edited. Most popular among those are Nanoletters ($IF_{2007}=9.6$), Nature Nanotechnology ($IF_{2007}=14.9$), Small ($IF_{2007}=6.4$)…

The group's seminal research strategy (led at that time by Prof. Christophe Vieu) was nanoaddressing- (*how to individually address nano-objects?*) and nanobiotechnology- (*how to individually address nano-objects in the frame of biology issues?*) oriented. The nanoaddressing issues were declined at three levels: mechanical addressing (led by Christian Bergaud), electrical addressing (led by Christophe Vieu) and optical addressing (led by Emmanuelle Daran).

Gradually, fitting to the evolution of state-of-the-art and of the local context (the Cancer-Bio-Santé competitivity pole), the group's philosophy mutates softly towards two new research directions: *micro(nano) systems for the biology* and *biology to create new micro(nano)biosystems*. In 2007, the group changes its name and becomes *NanoBioSystems*.

The group's size have strongly evolved since the creation; the human resources passed from 3 permanent researchers and 5 PhD students (in May 2002) to 6 permanent researchers, 10 PhD students and 3 post-doc fellows (in May 2009) and are expected to reach 8 permanent researchers, 12 PhD students and 3 post-doc fellows (in December 2009). It has to be noted that among our ex-PhD students, 4 doctors became CNRS researchers (Curie Institute, IMS Bordeaux, LAAS), 2 became Prof. Assistant (INSA Toulouse), 4 are R&D Engineers (Rhodia, Microbiochip, Infomil, Airbus), 4 are post-doc fellows abroad (EPFL, Academia Sinica,…).

From the daily organization point of view, there are 3 units (*teams*) standing as the operational pillars of the NanoBioSystems group: 2 of them are dealing with the micro(nano)systems for the biology item while the third one deals with both of the group's research directions, as previously defined.

The major scientific achievements during the 2005-2009 period of time will be briefly described in the following section.

Highlights and Major Achievements

Before digging deeper into the group's research highlights and corresponding major achievements, one should remind that two specific domains are explored by our members: micro(nano)systems for biology and biology to create new micro(nano)biosystems. Though there is no distinctive separation line in-between, we will separately describe them in the very next part only to ease the reading task.

Micro(Nano)Systems for the Biology

The fundamentals that are at stake here lie within the biosensing issue: new micro(nano)biosensor proofs-of-concept have to be sustained by integration of new materials and associated functions inside micro(nano)devices that will capture and sense one or several biological species due to specific functionalization steps of their active surfaces. For this to be successfully achieved, our group identified 4 major challenges to be addressed: *Integration*, *Functionalization*, *Sensing*, *Ultimate confinement*.

"Integration" — The state-of-the-art challenge in-here is related to successful cohabitation of actuation and sensing capabilities (piezoresistive, piezoelectric, capacitive…) in a unique microstructure [1]. "Successful cohabitation" traces the path towards an integrated sensor meeting the initial requirements at the end of the process flow (in terms of any kind of crosstalk avoidance between the actuation and

sensing modules, high sensitivity, high resolution, high signal-to-noise ratio…).

Our group demonstrated for the first time the sensing capabilities for small molecules (2,4-Dichlorophenoxyacetic acid used as common pesticide) of piezoelectric microsensors bearing a molecularly imprinted polymer (MIP) as capture layer [2]. The microsensors were silicon membranes with a piezoelectric thin film ($PbZrTiO_3$) for simultaneous actuation and detection of the mechanical resonances of the sensors (Figure 1).

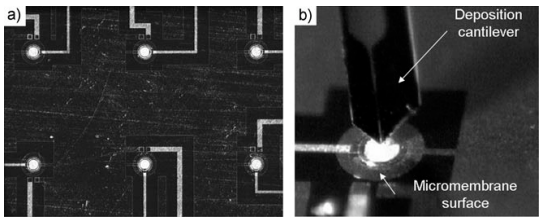

Figure 1: Images of a) a matrix of piezoelectric micromembranes with a global radius of 100 µm and b) a cantilever loaded with MIP precursor solution during deposition onto a micromembrane

The working principle was similar to quartz-crystal microbalances were added mass onto the quartz-crystal's surface provokes a shift into the resonant frequencies' values.

"Functionalization" — One fundamental question (that rapidly becomes a deadlock when developing microsensors for the biology) is how to functionalize micron-scale surfaces in a parallel way so as to spatially control the deposition of biomolecules onto solid surfaces. Having such ultimate functionalization tools would allow to fully taking benefit from the massive parallelization potential of microsensors arrays [3].

By developing the *Bioplume* automated spotter, our group demonstrated the micron-scale patterning (into the liquid phase) of multiple materials like polymers, biological species (DNA, proteins), metals, nanoparticles… One of Bioplume's successes was linked to self-assembly (under colloidal crystal shapes) of nanoparticles onto surfaces with different contact angles (Figure 2) [4].

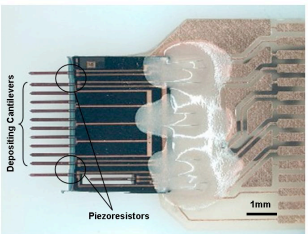

Figure 2: Optical photograph of the Bioplume silicon cantilever array bonded onto a PCB support

A direct relation between the spatial arrangement (2D or 3D) of the nanoparticles and the hydrophobic/hydrophilic feature of the surface has thus been determined.

Soft-Lithography (Micro-Contact Printing) has also been extensively developed for biochip applications. The group has demonstrated that DNA Micro-arrays patterned by µCP exhibit higher sensitivity than those patterned by conventional spotting technology [5]. A novel architecture of PDMS stamps called Macrostamp has been patented and enables the print of 800 different molecules in one printing step on a glass slide [6]. This technology is compatible with nanoscale pattern resolution and has been coupled to a label-free biodetection method based on light diffraction.

"Sensing" — The *Holy Grail* in the biosensing field is the highly specific detection of minute amounts (if not the unique molecule) of one kind of biological species diluted into "crude" samples – like human sera, environmental samples (*e.g.* polluted waters) etc [7].

This challenge has been addressed by our group meaning the fabrication and successful validation of interdigitated metallic nano-electrodes dedicated to bioassay applications [8]. The "unique molecule sensing" capability has been reached by demonstrating the detection of individual gold nanoparticles in real time. This has been achieved while monitoring the electrical conductance change (in liquid medium) of an array of nano-electrodes gradually bridged by nanoparticles landing onto their surface.

More recently a novel label-free optical biodetection scheme has been developed (the *DiffraChip* concept). The principle relies on the arrangement of probe molecules along a nanoscale periodic grating of lines and the monitoring of the 1st order diffracted light intensity. Upon specific probe/target interaction, this intensity changes and is used as the output signal. For submicronic patterns of lines, the intensity changes can be in the order of 100% making possible a label-free detection down to the *fM* range. This method has been patented and a prototype of biochip scanner based on diffraction is in progress.

"Ultimate confinement" — The active control of temperature on the micro- and nanoscale can be applied to study chemical or biological processes both from a thermodynamic or kinetic point of view. In order to evaluate the thermal behavior of new devices at small spatial and temporal scales, it is becoming clear that the performance of the current tools for thermal characterization has to be enhanced and that conceptually new approaches may have to be developed.

In this context, we have pursued the development of an improved methodology for fluorescent thermometry in dry and liquid conditions. The basic principle of fluorescent thermometry consists in measuring the temperature-dependent fluorescence of a fluorophore. This was experimentally demonstrated using various fluorescent nanoprobes (Rhodamine B, fluorescein, quantum dots), deposited on Joule-heated nickel nanowires [9] (see Figure 3). Rare-earth co-doped nanoparticles, synthesized by Michel Mortier Group at ENSCP in Paris, were also used as thermal nanoprobes to characterize nickel nanowires using an AFM-based configuration developed by L. Aigouy at ESPCI in Paris [10].

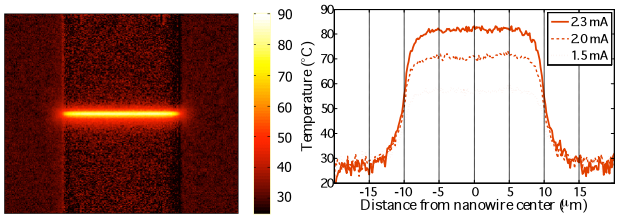

Figure 3: Thermal mapping of a Joule-heated nickel wire using Rhodamine B molecules as thermal nanoprobes (Wire length: 20 µm; width: 500 nm; thickness: 40 nm).

Biology to create new micro(nano)biosystems

This cutting-edge item is at the forefront of our group's research activities. Reinforced by the recent recruitment of Etienne Dague, an Atomic Force Microscopy expert with a Pharmacy background, this activity requires not only the intimate knowledge of the biological world but also the control of the self-assembly at the nanoscale onto prepatterned surfaces and the ability to precisely characterize such patterns. The fabrication of micro(nano)biosystems inspired from (or assisted by) the biology is more than basic research; at the long term, it aims at developing self-powered hybrid nanomachines able to carry out specific operations with biological (or medical) purposes.

The state-of-the-art challenges are to be separated into 3 directions: *Patterning*, *Assembling* and *Characterizing*.

"Patterning" — The need for elaborating engineered surfaces for assembling complexes architectures of molecules [11] or for assembling nanometric scale machines not in solution but on a surface has reinforced the interest of biopatterning using Micro-Contact printing. For biological applications or for advanced surface patterning, one main drawback of the technique is that only one type of molecule can be printed in one step because generally the stamp is inked everywhere with the same molecule. We have proposed a new method [12] for generating self-aligned patterns of different biomolecules in one imprinting step, using PDMS stamps exhibiting several levels of topography. By external pressure, the deformability of the PDMS stamp is used for bringing into contact with the surface the different levels of the stamp which have been selectively inked with the different biomolecules of interest (figure 4).

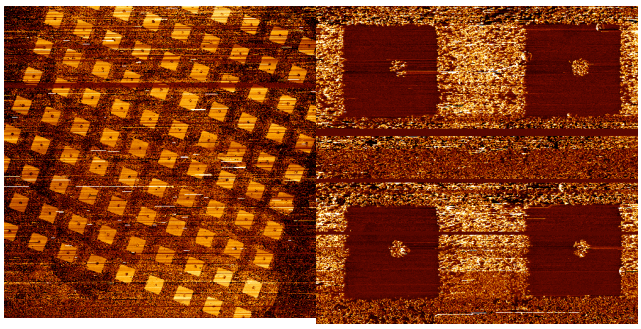

Figure 4: Liquid AFM image of self-aligned patterns of two different molecules. The middle dot is 1 µm size and is made of streptavidin proteins, while the large adjacent mesh is made of BSA proteins.

"Assembling" — By combining directed assembly using capillary forces [13] and Micro-Contact printing we have optimized a process for generating perfectly organized arrays of single DNA molecules stretched on a surface [14] (see figure 5). This process is crucial for improving the method of DNA combing used in genomics by assembling the DNA molecules precisely at registered positions.

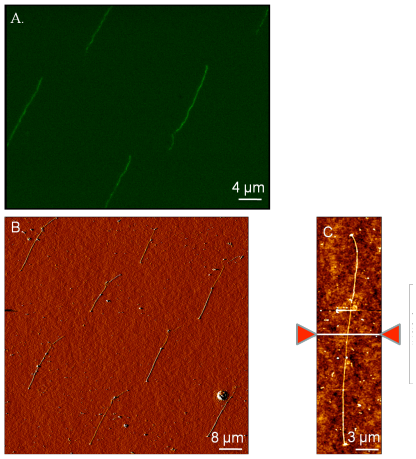

Figure 5: Fluorescence image (A) and AFM image in air (B) of highly ordered arrays of 30µm-long and 2nm-high phage lambda single DNA molecules printed on a (APTMS)-coated glass slide after Directed assembly on a micropatterned PDMS stamp. Zoom AFM image (C) of a single DNA molecule

Using a slightly modified protocol we have also demonstrated the capability to immobilize individual living bacteria at registered positions on a solid surface [15].

"Characterizing" — Using Atomic Force microscopy we are able to characterize living cells in their native liquid environment [16]. It is possible to

measure cell wall topography, qualitatively, and to quantify the roughness. Moreover, by using the force spectroscopy mode we can explore the nanomechanical properties of the cells while submit to a stress. We also develop experiments using chemical force spectroscopy. Here the AFM tip is coated by a chemical probe that can measure, hydrophobicity or electrostatic interactions etc as a function of the probe. Finally a new and exciting project consist in functionalizing tips by biological molecules such as anti body in order to localize receptors at the surface of living cells. The work has been conducted for now one year and a half on yeast, *L. lactis*, *E. coli*. [17] In the near future, we will start to characterize the interactions between bacteria and bacteriophages.

Significant projects and collaborations

A quite significant number of projects (mostly at the national level) and associated collaborations gave the Nanobiosystems group the opportunity to address all the issues previously discussed. They also allowed the group capitalizing interdisciplinary scientific and technological background which will be necessary on the path to success of its roadmap objectives (see *NanoBioSystems Project* document).

At the European level, the intense participation of the group in one integrated project (Emerging Nanopatterning Methods – *a.k.a.* NaPa in the 6th Framework Program, 2004-2008) and one Network of Excellence (NanoToLife, 2004-2008) allowed the major part of the *Integration*, *Functionalization* and *Assembling* developments.

At the national level, ANR projects (in the frame of PNANO calls) funded research work in the *Ultimate confinement* area (NANOTHERMOFLUO project), *Patterning* area (FLANAMO project), etc. Other national funding agencies (e.g. Army General Delegation) granted researches in the *Sensing* area.

At the regional level, foundations like InNaBioSanté allowed the group starting the Oncomate project in the *Functionalization* and *Sensing* areas.

If most of our partners are institutional (either in the same disciplinary field like IEMN Lille, IMRCP Toulouse, UTC Compiègne, LSLP-ESPCI Paris… or in different disciplinary areas as biology – IPBS Toulouse, Institut Curie Paris - and chemistry - UTC Compiègne…), we are thoroughly considering the industrial collaborations as instrumental for the success of our projects. This last consideration was key in the industrial valorization of the Bioplume concept (exploitation licence granted to Microbiochip company) in 2008.

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Photonics – PHOTO –

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Objectives and positioning

The Photonics research group carries out research on innovative concepts for photonic devices, to demonstrate novel devices with high performance as well as new functionalities. Current research activities target the challenge of photonic integration into systems, focusing on new materials, wavelength-scale structures such as photonic crystals and microcavities, innovative devices suitable for compact integration of photonic functions.

Topics covered include:
- semiconductor lasers, with vertical or horizontal architecture, as their performance and their integration with other components are of key importance for all photonic systems.
- novel photonic devices, exploiting in particular nanoscale optical phenomena not accessible before, and opening up new functionalities and advanced integration architectures.

Research activities range from level device architectures, over advanced fabrication processes, to efficient modeling and characterization methodologies.
The clean room facilities at LAAS including molecular beam epitaxy (MBE) machine, have allowed the group to develop in-house fabrication of GaAs-based photonic devices and to focus on these III-V alloys. Moreover, silicon technologies developed in LAAS have opened new opportunities in the field of silicon photonics.

During this last period, the activity was concentrated on:
- generic and innovative processes for the control of electrons and photons within the devices: MBE growth of nanostructures on patterned surfaces for ordered quantum dots and selective-area epitaxy, wet GaAlAs oxidation technology for precise lateral electro-optical confinement, polymer micro-optics suitable for self-aligned integration.
- advanced optical sources: spin polarized electron electroluminescent diodes, generic processes and simulation tools for high functional VCSELs and ridge lasers, 2D-based photonic-crystal lasers to demonstrate next generation lasers and to push away the limits of integration of the sources.
- novel architectures for advanced light filtering and detection using CMOS technologies.

Highlights and Major Achievements

Generic and innovative processes for development of optoelectronic devices

"MBE regrowth on patterned GaAs surfaces" — To localize particular zones at the (sub) micrometric scale (50nm-some µm) within the devices can be a major tool to develop new device design. We have investigated this key step in the case of GaAs surfaces, with the requirement to get uniformity for this process on large surfaces in view of the integration of that technology step within a device fabrication process flow. Clean and atomically-flat patterned GaAs surfaces were achieved thanks an original ex situ O_2:SF_6 microwave plasma treatment combined with an in-situ H-plasma treatment. [ACL553] MBE regrowth was successfully carried out on micro- and nano-stripes along the two perpendicular <011> directions. InAs quantum dot (QD) alignment was achieved along the [-110] stripes after growth of a 7nm-thick $Ga_{0.8}In_{0.2}As$ quantum well used as a stressor on 20nm buffer GaAs (Fig. 1).

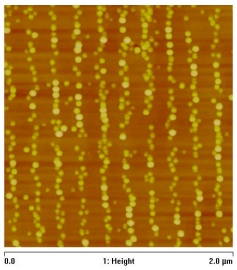

Figure 1: Aligned InAs QD formed upon growth on 7nm GaInAs stressor on oriented [-110] stripes nanopatterned in (001) GaAs

"Control of the AlOx/PAlOx for confinement" — To face up the increase in their application fields, laser emitters, including VCSELs, are moving rapidly towards greater integration capabilities, as well as diversified functionalities. Within this framework, we have focused our effort on the improvement and physical understanding of the wet GaAlAs oxidation technology. This process, known as AlOx, is nowadays largely used to fabricate high-performance single-mode VCSELs through the resulting electro-optical lateral confinement that it offers. We have investigated how to finely control the process and exploit it for 2-dimensional structuration of the

refractive index, and the electrical confinement. The kinetics of oxidation was thoroughly investigated in Al-rich AlGaAs digital alloys [ACL519]. Moreover, an original real-time in situ control of the oxidation front was proposed, leading to the development of a dedicated optimized oven that allows controlled size AlOx apertures to be achieved [ACL506]. The actual limit of the process is related to the lateral oxidation which hinders engineering capabilities. To overcome this, a derived oxidation technique applicable from the surface (through lithography) of a GaAlAs buried layer was proposed and demonstrated [ACL313] (Fig.2).

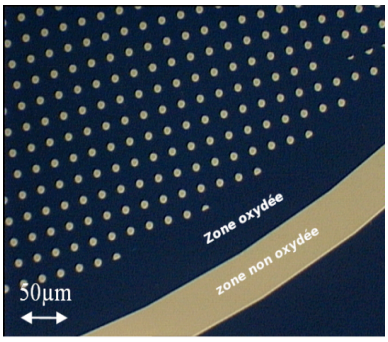

Figure 2: Free engineering of localized semiconductor areas in AlOx dielectric achieved from the surface thanks to the PAlOx process [patent WO2006/082322]

"Polymer micro-optics for VCSEL photonic integration" — VCSELs constitute now strategic light sources for optical communications as well as for instrumentation or sensing applications. Despite a limited far-field beam divergence, these sources have more and more to be associated with micro-optical components to enhance their performances or to increase their integration in systems [ACL377]. In this context, we have developed a new deposition technique based on a microcantilever-based spotter to fabricate polymer microlenses array. Spherical microlenses with good optical quality were demonstrated with a home-made thermocurable epoxy polymer [ACL309] (collaboration TONA-IR-VUB). Microlenses sizes achievable with this novel method were shown to be well suited for VCSEL beam collimation. In order to integrate such microlenses onto VCSEL devices, uniform thick SU-8 pedestals implementing different geometries and sizes were fabricated and their influence on the deposited microlenses was studied. A cylindrical shape was found to be the best suited to ensure a self-alignment of the polymer droplets on top of the pedestal (Fig.3).The application of this method to the monolithic integration of self-aligned polymer refractive microlenses on VCSELs has led to a significant reduction of the initial beam divergence (in the range [1-4°]) [ACTI1319]. The thermal reliability of these microlenses is now under study in collaboration with CIRIMAT laboratory and EADS Astrium (FIAB SU-8 project).

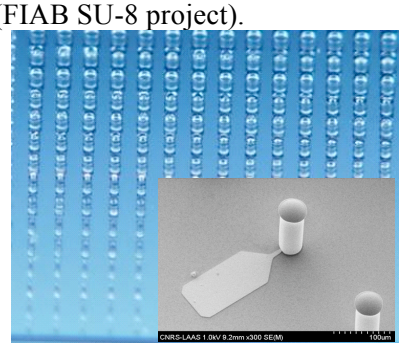

Figure 3: Microscope image of an array of cylindrical pedestals of various diameters [30-140µm] with self-aligned microlenses deposited on their surfaces. Insert: SEM image of a microlens integrated on a VCSEL device

2) Advanced devices

"Spin polarized electron electroluminescent diodes" — Efficient injection of spin polarized currents into semiconductors and sufficiently long spin relaxation times to manipulate or store the spin orientation of the injected carriers are the key issues for spintronic devices. QD-based devices are very promising for spintronics as the polarization of *p*-doped QD luminescence is directly related to electron spin polarization and because of their very long electron spin relaxation times. We have investigated QD p.i.n LED spin properties with INSAT (X. Marie Group) and the Unité Mixte de Physique CNRS/Thales (UMP/T, coll. H. Jaffrès et al) within the framework of a national program ACI Nanotechnologies [ACL274]. LAAS was in charge of the MBE growth of the Be-δ-doped QD-spin–light-emitting structure and of the fabrication of the spin-LED devices. An efficient electrical spin injection through Co/Al_2O_3 /GaAs structures into *p*-doped InAs/GaAs quantum dots embedded in the *p-i-n* GaAs light emitting diode was demonstrated. The electrical spin injection in the quantum dots is characterized by a figure of merit estimated to be at least 35%, considering an electron spin polarization of about 42% for Co, which was at the international state of the art. This was the first demonstration in France of the high potentialities of QD spin-devices [ACL285].

"Integrated photodetection in VCSELs" — We have investigated the lateral waveguiding properties of VCSELs for application to integrated power monitoring. Lateral light guiding has been modelled and demonstrated experimentally in standard VCSELs in which the cavity was preserved from dry etching [ACL9, ACL150]. Thanks to an original design including the use of a Schottky contact, the threshold and the thermal extinction of the lasing emission have been clearly identified on the lateral photodetected signal, with a monotonous increase of the photocurrent between threshold and extinction

suitable for VCSEL power monitoring. Finally, the involved transverse guiding mechanisms have been analytically described by extended (3x3) transfer matrices including sources of spontaneous emission [ACL266] in collaboration with Y.G. Boucher (ENIB-RESO).

"Electrical injection in broad-area VCSELs" — Improving the carrier injection uniformity in the case of broad-area surface emitting lasers is one of the challenges for electrically pumped VCSELs. LAAS has addressed this issue within the framework of FunFACS European project. For this purpose, we have tested, first, the addition of a spreading layer at the top of the device, using a transparent conductive electrode: ITO (Indium Tin Oxide), and, second, a multi-point localized injection associated with ITO (Fig.4).

We have shown by means of an electrical simulation tool that these generic solutions improve carrier injection into the multiple quantum wells zone, at a great degree for the latter. We have first optimized the deposition of ITO transparent conducting electrodes and have studied their electrical properties on GaAs in comparison with those of standard Ti-Au/GaAs contact. This study has highlighted a peculiar diffusion problem in ITO/Be-doped GaAs related to the post-treatment annealings needed for contact improvement. After annealing optimization, the interface contact resistance was measured to be only twice than that for the Ti-Au/GaAs contact. Finally, band-shaped devices emitting 50mW in a continuous-wave operation (CW) at room temperature have been demonstrated. These promising results have pointed out the needs for further improving the ITO/GaAs interface properties [ACL412]. They nevertheless demonstrated that these solutions can be exploited for the aimed application as well as for power generation or external cavity laser (VECSEL) realization.

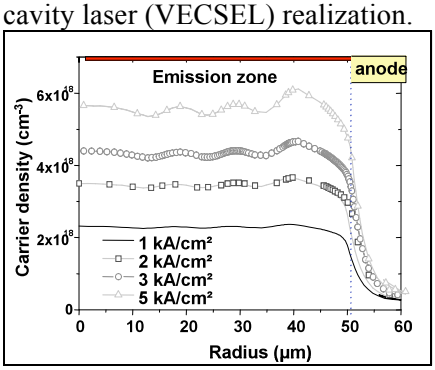

Figure 4: Electrical simulation of carrier density distribution in a VCSEL (half-device) with a multipoint-localized injection design associated to an ITO spreading layer for increasing applied current densities.

"General design tools and GaAs-based ridge laser processing" — Many optical systems depend on a high performance laser source. Only highly optimised, state of the art, devices are up to the highly demanding requirements of such systems. One challenge is then to analyse and predict performances of novel, not yet fully mature, laser diode technologies. To answer this problem, we develop new performance analysis methodologies based on the physical properties modelling and characterization of the devices. We applied such methods to assess radiation hardness of modern laser diodes such as Al-free QW laser diodes [ACL338] or quantum dash based laser diodes [ACL476].

Following this general methodology, GaInAsN/GaAs quantum wells have been studied and performed to extend the wavelength range of GaAs based laser diodes to telecommunication applications. We designed an optimized device structure to achieve a direct modulation up to a 10Gbits/s rate [ACL149]. We developed an original ridge structure based on an AlOx aperture to ensure both electrical and optical confinement (Fig.5) and we applied this generic process to fabricate a laser diode that exhibits a stable single-mode emission at 1.3 µm.

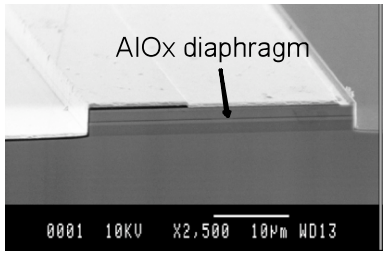

Figure 5: GaInAsN/GaAs AlOx ridge laser emitting at 1.3µm

"New laser cavities using 2D photonic crystals" — As an intermediate step between conventional waveguide lasers and all photonic crystals (PhC) lasers, we started research on single frequency tunable laser based on a "Coupled Cleaved Cavity" like geometry (C^3). We used an intra cavity 2D PhC mirror on the side of the ridge waveguide. We defined the mirror parameters to be in the PhC band gap and we designed the ridge itself to get the optimal confinement. We have developed a new complete process based on a combination of optical and electronic lithography and an inductively coupled plasma dry etching. This process was carried out on GaAlAs/GaAs structure and adapted on antimonide based layers within the ANR CRISPI project. The first results both on GaAs devices and GaSb based devices demonstrate lasing under CW operation. Further development should confirm the validity of this approach to get tunable single-mode laser diodes for absorption spectroscopy applications.

"Towards 2D all photonic-crystal semiconductor laser for planar integration" — 2D photonic crystals are of great interest for high Q nanolasers,

however they are not still incorporated in conventional lasers to exploit their extraordinary properties for next generation lasers. Moreover they could pave the way towards 2D planar integrated optics.

In the frame of the CRISTEL RNRT project, we have first investigated novel semiconductor lasers based on an electrically pumped 2D all PhC to explore the spectral potential of these lasers for access network applications. We have shown that an original affine deformation of the PhC lattice could allow a very smart engineering of the photonic band gap and of the DFB emission. Such designed devices, fabricated on InP system at III-V Lab, operated under CW electrical conditions and exhibited a stable single-mode DFB laser emission with a side mode suppression ratio as high as 36 dB, and a threshold current density of about 1.4 kA/cm² [ACTI1205].

In order to better explore the potential of such 2D PhC DFB lasers, we have then studied and fabricated edge laser sources emitting at 1µm, based on a 2D PhC GaAs membrane (Fig. 6). Using the previous affine deformation, we have demonstrated an ultrafine control of the emission wavelength under optical pumping with wavelength spacing as low as 0.025nm. [ACL532]. We have observed some dispersion on the results that we could attribute from a 3D analysis, to the coupling of the DFB modes or with PhC modes, and also to optical retroinjection effects at the mirrors. By tilting the mirrors and combining the affine deformation to a waveguide width variation, we will expect a tuning curve without spikes and a DFB mode with an extremely high quality factor [ACTI1138].

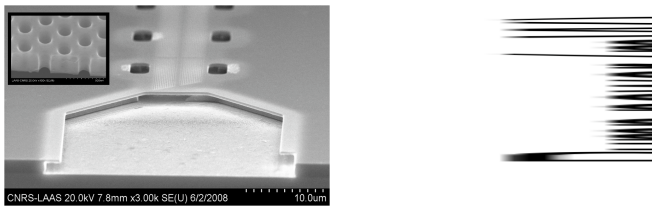

Figure 6: 2D PhC membrane laser and map of the emission spectrum as a function of the pumping power

We also focus on the challenge of an electrically pumped all PhC laser diode in the GaAs system at 850 nm. We have defined a masking method for high aspect ratio PhC entirely based on ICP technique. This approach has allowed etching of holes of 2.4µm in depth for diameters as small as 240nm in GaAlAs/GaAs[ACTN293] (Fig. 7).

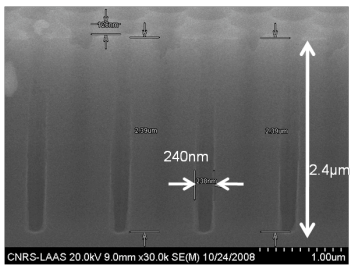

Figure 7: 2D PhCs etched in GaAlAs/GaAs

Since 2009, we took advantage of our well established membrane process to start activities in the random lasers field. This work completes our research activities on qualities and defects of PhC cavities.

CMOS-compatible photonic functions

Optical microsystem technologies and nanophotonics in association with CMOS-compatible processes offer the great advantage of miniaturization and new photonic functionalities. In this way, we successfully investigated detection and filtering functions, in the field of optical sensors and instrumentation.

"Optical phase-shift detector" — We proposed and demonstrated a new monolithic device which provides an innovating way of measuring the phase difference between two coherent beams propagating in free space [ACL120]. This device consists of a diffraction grating and a photodiode directly integrated in a single silicon chip by a CMOS-compatible process. For the first time, contrast as high as 75% was experimentally obtained in the range of 650 nm using a metallic grating characterized by a filling factor equal to 0.5. We demonstrated that contrasts higher than 90% can be achieved by optimizing the filling factor leading to a « smart » phase-shift measurement function that could be very useful in numerous integrated systems [patent PCT/FR2007/001914].

"Tunable Fabry-Perot micro-interferometer" — The studied device consisted of two parallel polysilicon adjustable mirrors monolithically integrated with a p^+n photodiode on a silicon substrate. In collaboration with IMT of Bucarest, and using an electro-mechanical simulation, we designed a test configuration of the tunable Fabry-Perot microcavity in order to optimize the system performance, considering both the steady-state behaviour and dynamic response (Fig. 8). Then, step by step, and with a particular attention on mirror/membrane fabrication, we studied the entire CMOS-compatible process to reach a tunability in a range of 60 nm around 800 nm by applying a voltage lower than 10 V.

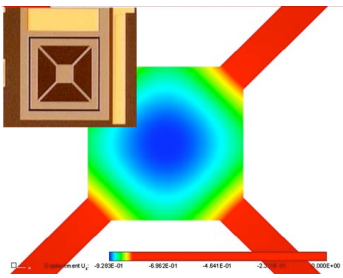

Figure 8: Deformation map on the central area of the movable mirror at maximum deflection. Inset: photograph of the top mirror/membrane integrated with a p^+n photodiode on silicon substrate.

"Nanophotonics for advanced optical filters" — Conventional spectral filters are based on Fabry-Perot structures and they now have reached intrinsic limits in terms of finesse and polarization independence while working at high incidence angles. In the frame of the ANR FOREAC project, and in collaboration with the Fresnel Institute, we studied an innovative way of filtering based on resonant grating filters. These are basically a periodically structured planar waveguide that specularly reflects and transmits light. For the first time, we experimentally demonstrated that reflection coefficients as high as 54% with a spectral width smaller than 0.4 nm can be reached in the 850 nm wavelength range by simple structures fabricated using a standard, C-MOS compatible, microelectronic processing [ACL293] (Fig.9). Moreover, we demonstrated that polarization independence for high oblique incidence filters can be reached by a careful design of 2D grating parameters. Quasi-polarization independence and narrow spectral response are also conserved when the angle of incidence is changed, giving rise to a large tunability, experimentally demonstrated to be larger than 10 nm under oblique incidence in the vicinity of 60° [ACL424]. The impact of technological limitations on the experimental performance has been identified from a thorough theoretical analysis [ACTI1490].

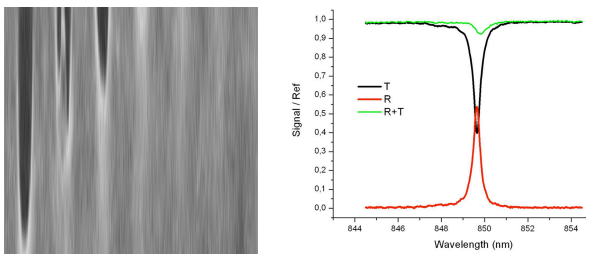

Figure 9: Left: SEM image of the surface of the filter (after 5 nm Au deposition); Right: experimental spectral response of the filter.

Significant projects and collaborations

- IST FunFACS, Optonanogen
- PAI Brancusi, Picasso, Orchid
- LIA Corée
- RMNT OSA131, RNRT AHTOS, RNRT CRISTEL
- ACI Nano SpinLED, ACI Nano Nanoacoustique ANR JC EELOT, ANR PNANO FOREAC, ANR CRISPI, ANR GLAD
- CNES
- FIAB-SU8 Projet Région Midi Pyrénées Recherche et Transfert de Technologie: EADS Astrium, CIRIMAT

Research domain
Modelling, Optimisation and Control of Systems – MOCOSY –

Scientific Topics

The Mocosy scientific area deals with uncertain dynamic systems within the framework of control and production systems. Observing, controlling and optimising such systems are approached at different levels of abstraction and along different architectures. The main key-words list as estimation, surveillance, diagnosis, state tracking, control, planning, scheduling, routing and, as a common factor, modelling. Strong links exist with the Applied Maths and the Artificial Intelligence (AI) fields.
The originality of the research stands on two features: it is guided by flexibility and robustness needs and it is positioned at the crossing of several scientific domains. The following topics come out from our expertise scope:

- Global and discrete optimization are approached by combining combinatorial optimisation from the Operations Research domain and constraint programming from the AI domain. It is applied to scheduling, planning and resource management and scaling problems. Heuristic and exact methods are proposed considering multi-objective routing problems or shortest path algorithms for multi-modal time-dependent systems, e.g. in the transportation domain. Non-convex optimization is also supported by the theoretical foundations of polynomial moments and algebraic geometry.
- Novel methods and algorithms based on Queueing Theory serve network optimization and quality of service evaluation. More applied research generates software tools for the analysis and optimization of communication networks.
- Diagnosis theories are investigated through original research that makes profit of approaches proposed in the control field and of logical model based diagnosis theories in the AI field. Continuous systems, discrete event systems, and hybrid systems are in the scope of interest. The properties for the design of diagnosable and self-healing systems are also in the core focus.
- Optimal state estimation for non linear and/or non gaussion systems lead to random and deterministic approaches to particle filtering, as well as work on Volterra non-linear filtering. Contributions to system identification and realisation count with an original method for linear and bilinear dynamic systems, relying on an hereditary output predictor, i.e. whose memory increases with data growth. Diffusive representation and non linear operators add to the modeling and representation tools.
- Control theories for linear and non-linear systems are contributed with emphasis on constructive methods and synthesis of structured control laws in state space or frequential frameworks. Original results can be outlined for the multi-objective linear structured control problem, the windup problem, the design of control laws for periodic or hybrid systems, PDEs.

The Research Groups

The MOCOSY scientific area federates the activities of four research groups. The observation and its interpretations in terms of state estimation, fault detection and diagnosis are the focus of the ***Diagnosis and Supervisory Control*** (DISCO) research group whose spectrum covers continuous, discrete events and hybrid systems. The ***Modelling and Control of Networks and Signals*** (MRS) research group is also interested in state estimation and stochastic model based filtering methods with special emphasis on nonlinear methods. Stochastic models are also used for the modelling, optimisation and supervision of networks. The sets of tasks that intend to close the loop and act on the system are organized in two levels. On the one hand, the synthesis of advanced control laws that account for uncertainties, disturbancies and non-linearities at the level of continuous dynamics is considered in the ***Methods and Algorithms in Control*** (MAC), leading to contribution to convex and non convex optimization. On the other hand, the ***Modelling, Optimisation and Integrated Management of Systems of Activities*** (MOGISA) research group has an upstream activity on combinatorial optimization and provides solutions to production planning, task scheduling, transportation systems, and resource allocation problems.
The Mocosy area is actively involved in the national programs such as GdR MACS, I3, ISI and RO and the international programs, though exchange programs and bilateral collaborations.
It has generated the Spin-off QoS Design (www.qosdesign.com), which proposes solutions for modelling and supervising telecommunication networks.

The Main Application Domains

The generic nature of our research means it is of value to numerous application domains that are approached through industrial partnership. Our main

collaborations refer to aeronautics and space, automotive and transports, telecom networks, defense, biology and health, involving us strongly in the two Competitivity Networks of the Midi-Pyrénées region “Aeronautics, Space, and Embedded Systems” and “Cancer, Bio, Health”. In addition, our research is instantiated at the European level through several projects.

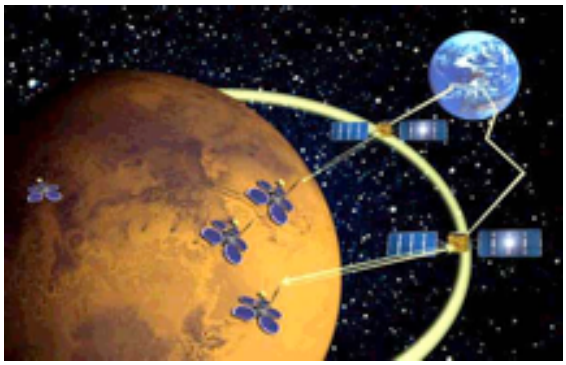

Figure 1 : Space domain: Planning of communications in a planetary exploration mission; orbit and attitude control; Diagnosis in an architecture for autonomy

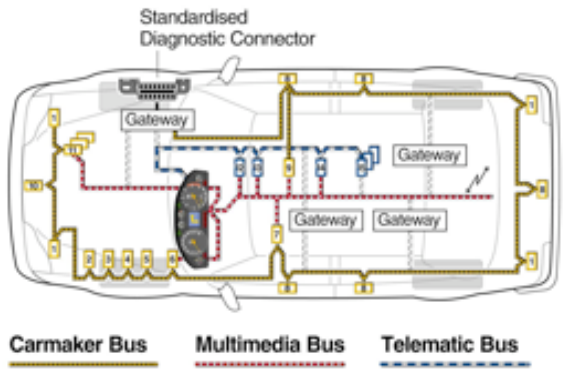

Figure 2: Automotive domain: on board diagnosis of distributed functions; test sequencing for workshop diagnosis

Diagnosis and Supervisory Control – DISCO –

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Objectives and positioning

Availability, sustainability and safety are key properties for modern systems. These properties require special attention for the tasks of diagnostic and supervision, that is surveillance and health monitoring on one hand, and associated decisional processes on the other hand. In biological systems, diagnosis can also prove a useful task, allowing the interpretation of massive amounts of data and the emergence of hidden knowledge.

The DISCO research group considers the qualitative aspects of supervision and their integration with the continuous dynamics of systems. Thus part of the activity deals with hybrid systems and the interface between continuous signals and their abstracted interpretations, in symbolic or event-based forms. Formalisms borrowed from developments in Artificial Intelligence naturally connect with continuous and discrete models from the Control community, as well as with machine learning and classification techniques. This multidisciplinary approach and the wide spectrum of classes of systems are the trademarks of the group, whose works are recognized in both communities.

Highlights and Major Achievements

Model-based diagnosis

Two distinct and parallel research communities have been working along the lines of the model-based diagnosis approach: the FDI community and the DX community that evolve in the fields of Automatic Control and Artificial Intelligence, respectively. The DISCO group works along the two lines. The links between the approaches have been clarified[1] and interesting synergies have been outlined, to which DISCO also contributes.

"Extensions of the theory of logical model-based diagnosis" — In the original model-based diagnosis logical theory, diagnoses are sets of components for which the hypothesis of abnormal behavior is consistent with the model and with observations. Reiter[2] showed that (minimal) diagnoses are given by the hitting sets of the set of (minimal) conflicts. A hitting set of a collection of sets is a set intersecting every set of this collection. The HS-tree algorithm was originally proposed by Reiter. It generates all the minimal hitting sets based on a set of conflicts.

The HS-tree algorithm has been extended keeping the tree structure to manage component *time labels*. It takes as input time labelled conflicts and outputs time labelled diagnoses that are updated in time when new conflicts are exhibited (ACTI840, ACTI871).The generalisation of this work leads to components with convex or non-convex, bounded or unbounded continuous attributes. This framework generalizes the model-based diagnosis logical theory to continuous spaces. The algorithm *Continuous Hitting Sets* (CHS) provides diagnoses from conflict sets of components with continuous attributes (ACTI1220).

"Consistency-based Diagnosis of discrete-event systems (DES)" — In classical consistency-based approaches for diagnosis, an inconsistency between the models and the observations is interpreted as a fault occurrence. We proposed to enhance this traditional interpretation by including modelling errors. Our proposal addresses the problem of inconsistency discrimination: fault versus modelling error. The diagnosis problem is then tackled via consistency restoring by modifying the models so that they match the observed behaviour (ACTI839).

Another work has considered the fact that acquiring fault models is often a problem. The diagnoser approach[3] is very well suited to an embedded context but requires the knowledge of such behavioural fault models. Our proposal has two main features: (i) a generic model of intermittent faults (spurious or missing events) is used in order to represent classes of faulty behaviours (ACTI532) (ii) the Petri net formalism avoids the exhaustive generation of the state space of the model (ACTI595-803). This approach has been applied in the automotive domain

1 M.O.Cordier, P.Dague, F.Levy, J.Montmain, M.Staroswiecki, L.Travé-Massuyès, Conflicts versus analytical redundancy relations: a comparative analysis of the model-based diagnosis approach from the artificial intelligence and automatic contro perspectives. IEEE Transactions on SMC. Part B, Vol.34, N°5, pp.2163-2177, Octobre 2004.

2 R. Reiter "A theory of diagnosis from first principles", Artificial Intelligence 32(1), p. 57-96, 1987.

3 M. Sampath & al. Failures diagnosis using discrete events model, IEEE transactions on control systems technology, vol. 4, no2, pp. 105-124, 1996.

within the frame of the *Laboratoire Commun AUTODIAG* (ACL592, ACTI1012).

"Diagnosis and state tracking of hybrid systems" Hybrid systems serve as a powerful modeling paradigm for representing complex continuous controlled systems that exhibit discrete switches in their dynamics. Diagnosing such systems has been at the core of three main pieces of work.

The first work follows a multi-model state estimation approach, considering a model in the form of a hybrid automaton. The system and the models of the system are non deterministic. Bayesian belief update approaches to stochastic hybrid system state estimation face a blow up in the number of state estimates. These limitations can be avoided by using bounded intervals to represent the state uncertainty and hence splitting the continuous state space into a finite set of possibly overlapping geometrical regions that together with the system modes form configurations of the hybrid system. As a consequence, the true system state can be captured by a finite number of hybrid configurations. A set of dedicated algorithms is proposed that can compute these configurations efficiently[4].

Another work proposes the estimation of the system mode (ACTI1244) and an analysis of diagnosability (ACTI1219) (cf. Section 3). The approach is based on extensions of the parity space method and allows the association of signatures to each of the operating modes of the system. Changes in the signature that result from switches among operating modes are abstracted in an event-based form. The tracking of the set of events allows the determination of a belief state over the current operating mode of the system, i.e. a diagnosis. This work has been pursued for proposing policies for active diagnosis, guided by its diagnosability (ACTI1544).

Another solution is to abstract the continuous behavior of the system by a set of qualitative constraints (i.e. constraints over discrete variables). The diagnosis and state-tracking problems can then be formulated as a Constraint Satisfaction Problem. The structure of these problems is exploited to propose efficient algorithms tailored for on-board applications (ACTI1533). The computational efficiency of the method is improved by using a hierarchical behaviour model of the system, based on proper abstractions (ACTI772, ACTI801). This fits the modern embedded architectures that are layerized into subsystems and functions.

Finally, a combined model-based and data-driven methodology has been developed. It relies on a *reference model* for simulation and state estimation using a hybrid dynamic systems simulation package (*PrODHyS)* which is based on *Object Differential Petri Nets (ODPN)*. Diagnosis includes three steps: Kalman filter based state estimation, signature generation, signature comparison (ACL501, ACTI426, ACTI679, ACTI728). The coupling of fuzzy classification with hybrid simulation puts together forward reasoning to identify the fault and backward reasoning to go back to the occurrence of the fault (ACTI637, ACTI1195). This approach leads to a library integrated in *PrODHyS* and developed within the *Laboratoire de Génie Chimique* of Toulouse (ACTI1200, ACTI1503).

"Active diagnosis of hybrid systems and DES" — On-line diagnosis must accommodate the existing sensoring capabilities of a system, which often results in limited diagnosability. However, although faults may not be always discriminable, there are generally operating modes of the system in which they are. Active diagnosis relies on (autonomously) applying specific inputs to the system so as to exhibit additional symptoms that help refining the diagnosis (ACTI1291).

The idea is to use the diagnosability properties to drive the system towards modes with increased diagnosability with respect of safety considerations. A finite state machine called the active diagnoser has been proposed and formally defined. The active diagnosis problem is then formulated as a conditional planning problem (ACTI1544). Hence, the active diagnoser is transformed in an AND-OR graph and active diagnosis plans are computed by an appropriate graph exploration algorithm (ACTI1521, ACTI1541).

"Off-line Hierarchical diagnosis" — In the domain of off-line diagnosis, e.g. in car repair workshops, the main problem is the determination of a proper sequence of tests and measures at available control points, which would lead to greedily localize the fault quickly and at the lowest cost. This problem is known as the Test Sequencing Problem.

The developed method uses techniques in hybrid system simulation (based on the Modelica language) to build a dictionary of fault signatures. We make the most of this dictionary either by heuristic optimization techniques or via the computation of the entropy of a test that yields a measure of its expected quantity of information. Hierarchical multi-model strategies allow us to structure the search space by articulating functional observations with low level signal measures, so that proposed tests best match expert human intuition (ACTI525, ACTI530).

"Set membership estimation and detection in continuous systems" — Set membership parameter and state estimation methods are interesting alternatives to stochastic model based estimation

[4] *E. Benazera, L. Travé-Massuyès, Set-theoretic estimation of hybrid system configurations, IEEE Trans. SMC Part B: Cybernetics, Vol.39, N°5, pp.1277-1291, Octobre 2009.*

methods when disturbances and noises are assumed to be bounded but otherwise unknown.
We successfully tested a state estimation approach on an aerodynamic model of a glider longitudinal motion and on an aeronautic test bench. The prediction step computes a rough enclosure of the state variable vector while the corrector step inverses the output function allowing us to refine the prediction. The prediction step is based on a Taylor expansion for which we proposed an original way to compute an enclosure of the rest. The correction step uses the SIVIA (Set Inversion Via Interval Analysis) algorithm (ACTI879, ACTI1290).
We also tested a parameter estimation approach on control surface oscillatory failure detection (also using SIVIA) that identifies the parameters of the oscillatory failures. The method proves efficiently the non-existence of a fault. A stochastic approach would conclude to the existence with a tiny confidence range, which is much more difficult to interpret.

"Observer based methods" — A method for isolation and identification of singular faults for nonlinear continuous dynamic systems has been devised. It is based on the characteristic of monotonicity of the observer prediction error according to the difference of the parameters (ACTI583). It was performed using an interval based adaptive observer. The admissible values of each parameter are subdivided in several intervals and an isolation observer is built for each interval (ACL251, ACL336). For sensor and actuator faults, we focused on additive faults. The algorithm considers the actuators faults and consists of two banks of adaptive observers to isolate faults. The first bank is devoted to fault detection and identification; the second one is based on candidates values obtained from the previous observers (ACTI1344). The method detects, isolates and identifies simple, multiple and simultaneous faults (ACTI1446).
A new architecture of FDI / FTC has been proposed; if a fault occurs, the FDI algorithm detects it, and determines its location and size. Using this information, an algorithm switches between several controllers, ensuring stability and keeping the system close to the desired state (ACTI1154, ACTI1166).

"Modeling and fault detection based on differential operators" — Methods based on differential operators have proved relevant to tackle the complexity of dynamic non linear systems, e.g. spatially distributed or highly non linear. We proposed a theoretical framework based on global trajectory descriptions for modeling, analysis and resolution of such problems by using suitable operatorial transformations such as time-scale transformations, diffusive representation, operatorial parametrization, with the aim of transforming the problems into simpler ones. This approach has been successfully applied to build numerical schemes for a wide class of integrodifferential wave equations (ACL479, ACTI1245, ACL429), to identification of MEMS models, and to the problem of control of fed-batch bioreactor model (ACTI1060, ACTI1246).
Methods for fault detection in differentially flat systems have also been investigated. The differential flatness property is characterized by relations that allow expressing the system states and inputs as functions of their flat outputs and their derivatives. Notions like minimality of flat outputs, strict flatness and additional degree of redundancy have been defined. This has led to the proposal of a global fault detection method based on flatness, which has been successfully tested on an aeronautic application (ACTI528, ACTI671).

Diagnosis and supervision based on machine learning methods

"Classification approaches" — In some domains, the knowledge is so badly formalized that data driven methods are preferable to model-based approaches. A method based on the elaboration of a new data space partition quality index (ACTI618) including a measure of inter-class distance and partition dispersion has been proposed. It finds the optimal partition in terms of compactness and class separation (for better discriminability) only from the membership degree matrix generated during a previous/initial classification. Its application has been illustrated on academic benchmarks and on 3 chemical processes (ACTI1542).
In parallel, studies with a more practical scope have been performed for the development of a supervisory/diagnosis system in the field of potable water production processes in collaboration with the SMAPA company in Mexico (ACTI1464) and the Rocade station at Marrakech in Morocco (ACL64, ACLN28). Beside the elaboration of the monitoring/diagnosis classification based system including a developed software sensor based on neural networks for the coagulation process control (ACTI1464), a generic technique for the automatic validation of state transitions based on the membership degree analysis has been developed and applied (ACTI791).
Our participation to 3 research projects and the emergence of a new application domain: cancer diagnosis (see *Diagnosis and therapy* in the perspective report) demonstrate the genericity of these works.

"Syntactic similarity metrics" — A promising piece of work has approached the development of models as the solution to a min-max problem, in the frame of finding a probability model that permits encoding of data with the shortest mean code length.

For a parametric class of probability models there is a universal parameter-free model as a density function measuring its complexity. The complexity is defined in terms of the least number of bits it takes to write down the data. This has been proposed as a methodology for fault diagnosis in automotive systems based on logfile analysis. The proposed metric, based on Kolmogorov complexity, measures the similarity of log files. Such a similarity metric is attractive because it does not rely on any detailed knowledge about the nature of the data.

"Relational machine learning for diagnosis" — In the case of complex systems such as in biological and biotechnological, a recent approach uses classification tools and relational machine learning that permit emergence of information. Deductive models are too limited for describing their behaviours in a dynamic environment. However, if causal knowledge is modelled and exploited through deductive/inductive reasoning, taxonomical knowledge and heuristics can be exploited in an abductive phase. The idea is to apply techniques from classification and Logic Inductive Programming to find the relevant parameters that yield simple logical explanations. This will be codified in a vector used to diagnose the system (ACTI535).

Properties and diagnosis-oriented design

"Diagnosability" — Diagnosability analysis allows one finding the reasons why an algorithm cannot diagnose some situations (ACTI674), as well as ways to improve the degree of diagnosability by recommending additional sensors (ACTI1017).

In the context of model-based diagnosability analysis, we first proposed a framework based on classical logic that takes into account the distributed nature of a system by propagating pieces of information among the different components. Tests have been performed on a Web Service architecture in the context of the European project WS-DIAMOND (ACTI729). We also defined a formal framework to recommend about sensor placements and the type of diagnostic architecture guaranteeing a diagnosability degree (ACTI1017) for distributed DES. This method, developed in the context of aircraft maintenance in the ARCHISTIC project (ACTI1309), relies on local diagnosability and diagnosis accuracy (ACTI519) and aims at minimizing the total cost of the system design to achieve a given diagnosability degree. We also characterized the diagnosability of hybrid systems by considering them as the composition of underlying discrete-event and continuous multimode systems (ACTI1219). This provides a new characterization of diagnosability for continuous multimode systems and leads to the definition of necessary and sufficient conditions for diagnosability of hybrid systems. We showed that diagnostic algorithms applied to hybrid systems have better capabilities than algorithms independently relying on the discrete-event and continuous parts (ACTI1244). Finally, we investigated the diagnosability of temporized systems and analyzed the diagnostic capabilities of an algorithm based on the recognition of temporal event constraints (chronicles). Our method relies on reachability analyses of timed petri nets and has been tested in the WS-DIAMOND European project (ACL354).

When a mathematical model of the system is not available, we proposed a methodology based on information theory (Shannon's entropy), which associates measurement and data classification techniques. The method takes time sensored data resulting from failure scenarios as input and identifies the most relevant sensors with regards to information wealth and discrimination power. Feasibility tests have been carried out on industrial cases (ACL349, ACL370, ACL369) and were part of a project supported by the "Institut pour une Culture de Sécurité Industrielle".

"Extensions of diagnosability and unification for state-based and event-based systems" — Model-based diagnosis approaches for state-based systems and event-based systems have been developed in distinct and parallel tracks. We propose to clarify the correspondences between the concepts used in each approach and show that diagnosability can be unified using the concept of signature, for which a new definition is provided for EBS. These results bridge SBS and EBS diagnosability and open perspectives for hybrid model-based diagnosis.

We proposed a properly extended definition of diagnosability, that applies not only to fault modes but to any property that can be mapped to a set of system states. For repair precondition properties, the extention leads to *self-healability* that clearly states the necessary links between diagnosability and repairability. An algorithm was proposed for the verification of self-healability, and strategies are defined for helping system designers to make their system self-healable.

Fault management architectures

"Architectures for autonomy" — Autonomy is the ability to independently perform decisions and act in a changing environment.

A common view holds a clear separation between the act of diagnosing and that of planning/controlling. Our proposal relies on three modules cooperating at the decision level. The active diagnoser detects situations where an active diagnosis session must be triggered. The planner for diagnosis computes a tree plan for refining the diagnosis. The mission planner computes a mission plan. These tasks have been

integrated in an on-board architecture. An execution control level based on Petri nets is used for specifying the links between them and to manage conflicts that could appear.
Another way to go consists in capturing diagnosis into planning thanks to partially observable Markov decision processes (POMDPs). If there is any gain to be made by avoiding or mitigating certain faulty effects, the solution of a POMDP would capture it in its optimal policy.
In the case of web Services, we concentrated on the the development of a platform supporting the self-

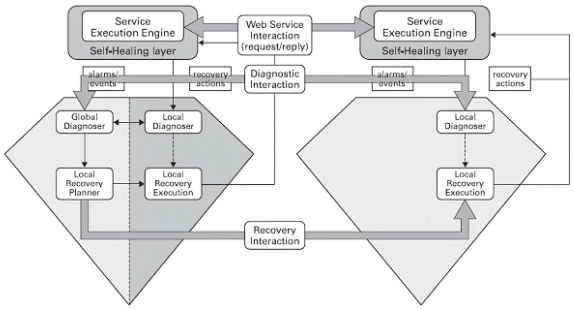

Figure1: Overall Architecture

healing execution. A "diamond" module (in charge of the enhanced service execution and monitoring, diagnosis and recovery planning) is associated with each service and with the orchestrator (cf. Figure 1).

"Architectures for maintenance" — Nowadays, system maintenance is a key challenge when complex systems are involved (aircraft, cars…). Accurate diagnoses (via on-board health monitoring) and prognoses optimize the maintenance and go towards preventive maintenance. This has been showed in the ARCHISTIC project in which we proposed a generic health monitoring architecture (ACTI1347). Prognosis predicts future fault modes relying on ageing models. The architecture copes with the heterogeneity of the system components and the self-maintainability requirements (on-line diagnosis and planning).
One particular example of a prognostic function has been proposed for the degradation of hydraulic actuators of aircraft turbine engines in the TATEM European project. The main result consists in the development of an ageing index called LPI (Linear Parametric Image) based on the estimation of the parameters of a fictive linear model, a SISO transfer function. The comparison of this index with the one when the device is new gives an image of the degradation.

Significant projects and collaborations

Acronym: Title — Partners — Website	Period
AUTODIAG Common Laboratory — IRIT, ACTIA	2005-2008
ARCHISTIC: Architecture for distributed diagnosis and prognostic, within AIRSYS common laboratory — AIRBUS	2007-2009
SIRASAS: Stratégies Innovantes et Robustes pour l'Autonomie des Systèmes Aéronautiques et Spatiaux — IMS, SATIE, CRAN, LRI, ONERA, CNES, Thalès Alenia Space, AIRBUS	2007-2010
Knowledge-based Discovery in Systems Biology — NII Tokyo — French-Japanese CNRS-JST cooperation program	2006-2009
Diagnostic actif et reconfiguration embarqués : application aux satellites autonomes — Thalès Alenia Space	2005-2008
Surveillance, diagnostic et pronostic en temps réel de systèmes hybrides : application à des bancs d'essais — CERTIA	2006-2009
AGATA: Etudes et architectures pour l'autonomie et le diagnostic — CNES, ONERA	2005-2008
WS-DIAMOND: Web Services - DIAgnosability, MONitoring and Diagnosis — Universita di Torino (Italy), Politecnico di Milano (Italy), Université de Rennes 1, IRISA (France), Universität Klagenfurt (Germany), LRI Université d'Orsay (France), Vrije Universiteit Amsterdam (The Netherlands)	2005-2008
TATEM: Vieillissement des équipements hydromécaniques des réacteurs — Hispano Suiza	2004-2008
ADES: Estimations ensemblistes de systèmes dynamiques et application à la détection de fautes — ECS, LAPS, LIRMM-CNRS	2007
SUPERCOM — Supervision of Composite Systems — National ICT of Autralia	2006-2007
Développement d'un réacteur intensifié continu en carbure de silicium pour la synthèse d'un principe actif	2006-2008
INPAC — Pierre Fabre, BOOSTEC, LGC, LAAS-MIS	2007-2010
Interaction dynamique entre les phénomènes biologiques et physiques pour la maîtrise des performances des bioprocédés — LBB/INSA	2005-2008
Modélisation des dynamiques microbiennes par systèmes multi-agents adaptatifs intégrant les données macroscopiques et moléculaires — LBB/INSA, LPS/UPS, SMAC/IRIT	2005-2008
DIAPA: Diagnostic Automobile par Apprentissage — LAAS-N2IS, HEUDIASYC-CNRS, PSA Peugeot Citroën, Delphi, Freescale, Serma Ingénierie	2007-2010
Automatisation Intégrée des Procédés de Production — Universidade de Los Andes, Venezuela	2005-2009
ROSACE: RObots et Systèmes Auto-adaptatifs Communiquants Embarqués (RObots and self-adaptive Embedded Communicating Systems) — ONERA, IRIT	2008-2012
Nouvelles applications dans le domaine de la sécurité industrielle et du REX de systèmes d'aide à la conduite supervisée, d'abstraction d'informations, d'analyse et de classification de données (ICSI – AO – 2003 – 11)	2004-2006

Modeling and control of Networks and Signals – MRS –

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Objectives and positioning

The MRS group deals with the development of new methods and algorithmic approaches to analyze, design and evaluate the performances of telecommunication networks and systems. It is also concerned with advanced signal processing and systems modeling and control. The group conducts different research projects on traffic modeling, optimization and network planning, cluster or grid computing systems, non linear filtering applied to signal, Volterra filtering, non linear systems realization and identification via hereditary algorithms and diffusive representation. The group collaborates with many academic research teams, both national (INRIA and I3S in Sophia Antipolis, ENST in Paris and ISIMA in Clermond-Ferrand) and international (CWI in Amsterdam, HUT in Helsinki and the California Institute of Technology in Pasadena, AIST in Japan). In addition we also have long lasting collaborations with several industrial partners like SFR, Index Multimedia, AIRBUS, FT R&D, Alcatel, Thales, DCNS, NavoCap, and QoS Design.

Highlights and Major Achievements

The group aims at contributing with both fundamental and applied results. The research conducted covers two axes:

- Analysis, Design and Performance Evaluation of Telecommunication Networks and Computer Systems;
- Signal Processing and Systems Identification and Realization.

Our main theoretic tool will be stochastic modelling and analysis. Stochastic modelling and analysis has been a popular method for analyzing the behaviour of algorithms in complex networks. Indeed, randomness is inherent in the network. For example, the behaviour of Internet users –when they connect, what they download, when they disconnect– is random. Moreover, changes in topology either due to user mobility or due to faults are random as well. Thus, stochastic methods are well suited for analyzing networks of this type.

Specifically, within the broad range of stochastic methods we shall primarily use tools from queuing theory, stochastic scheduling theory, and game theory. Stochastic scheduling theory is the study of resource allocation algorithms in a network of queues, and would be useful in predicting the performance of the proposed algorithms. The choice of game-theoretic techniques is complementary to stochastic methods and natural as well. Game theory is the study of optimal decentralized decision-making process when several independent agents interact in order to minimize their own cost. In the environment of the Internet, the end-users and routers can be thought of as agents who need to make decisions.

In the next 2 sections we describe in more detail the research problems that team members are working on:

Analysis, Design and Performance Evaluation of Telecommunication Networks and Computer Systems

In recent years, the use of both the Internet and wireless services has experienced an explosive growth. Network operators and service providers anticipate further expansion, fueled by the emergence of all-optical networking as well as the convergence of wireless and Internet access, along with a fundamental trend towards service integration. It is expected that future information and communication systems will accommodate a variety of new applications with a diverse range of Quality-of-Service (QoS) requirements. These observations have raised the need for the development and analysis of mathematical models to predict and control the QoS of information and communication systems, including wired and wireless networks and large-scale distributed systems. Within this area, our scientific contributions are both theoretical, with the development of new modeling formalisms, and applied, with the development of software tools. The research activities in the last four years have focused on the following themes:

"Modeling and enhancement of TCP" — TCP is the protocol that carries most of the data on the Internet. We have developed mathematical models that capture the transient and stationary behaviour of TCP [ACTI843] and we propose modifications, in

collaboration with standardization bodies like the IETF, in order to improve the performance of TCP (see [AAA+09]).

"Simulation of Large-Scale Networks" — One of the major achievements in this area is the development of the differential traffic modelling theory for the simulation of large-scale communication networks. Differential traffic theory has also been extended to the patented innovative concept of hybrid simulation, a global theoretical framework allowing to combine analytical models and event-driven simulation models . We have also obtained a new analytical approximation of the jitter incurred by CBR traffics in IP networks [ACL172]. More recently, we proposed a new flow-level modelling of TCP traffics using GPS queueing networks [BAG09], [ACTI1025].

"Queueing Theory and Scheduling Theory" — The performance obtained by a set of jobs that share a common resource can substantially be improved by deploying an appropriate scheduling policy. In this line of research, we have applied results from queueing and scheduling theory, to determine and develop optimal distributed protocols in order to share the resources of a network among the concurrent flows. In particular we have obtained a unifying conservation laws that applied to wide range of single server queueing systems [A07]. In the last two years we have extensively worked on characterizing the opimal scheduling discipline in a single server queue [AAR09].

"Network Optimisation" — The group has a long experience in optimisation theory, mainly focused on network design and planning problems. In the last years our research has mainly dealt with IGP weight optimization [ACTI200] and with traffic matrix inference from link counts [ACTI657]. More recently, we proposed new approaches for access and backbone network design [ACTI1288] [BHBG09] as well as for network dimensionning [FBBHG09].

"Distributed Systems and Grid Computing" — Based on measures obtained through a potentially intrusive instrumentation of parallel programs (source code annotations, post-mortem logs analysis), we develop mathematical models of distributed applications in order to predict their processing times. Such models are used for dynamic task mapping on the nodes of a computational grid. Applications are in the field of electromagnetic simulation and distributed. We refer to [ACTI768] for more details on this line of research. The autonomic computing is a response of the increasing complexity of grid utilization. The goal is to give to the final user a simply way to deploy, administrate and describe dynamic evolution of a parallel application. We use UML description and more precisely their activity diagrams to create a model representing the dynamic of the system. The TUNe tool created at Toulouse University is used to experiment those works on an electromagnetic simulation [ACTI1513].

"Game Theory applied to the design of Distributed Algorithms" — In the design of distributed algorithms, a key measure of efficiency and robustness is the so-called "Price of Anarchy" (PoA) which measures how far the worst-case Nash equilibrium point is from the global optimum. An algorithm that is robust to parameter changes will be able to follow the trend in the global optimum by keeping PoA bounded, thus guaranteeing a certain system performance. In [AAP08] we have shown that for certain routing games the PoA is unbounded. In such situations, the system designer should be aware of the set of the system parameters for which the performance can degrade significantly. In [ABP09] we have investigated the impact of selfish users (=network operators) on the performance of a large scale network.

Signal Processing and Systems Realization

The group has a long-term tradition in the non-linear domain as well as that of infinite dimension. One may distinguish:

"Numerical filtering techniques" — The particle filtering technique was developed through industrial collaboration for Defense applications as soon as 1989. It has given rise, during the past ten years, to purely deterministic versions, which supersede the old random technique or Monte-Carlo type. More precisely, the Monte-Carlo simulation of the dynamic model noise is replaced by a deterministic exploration, as it is the case in the classical Gaussian mixture technique (1970). This allows revisiting classical Defense applications such as RADAR, SONAR, GPS or Telecommunications [ACTI368] [ACTI374], with significant performance improvement. In addition, new results in Simultaneous Localization and Mapping (SLAM) and moving objects tracking with monocular vision have been obtained using this approach (collaboration with the LAAS RAP team) [ACL485] [ACTI682]. Besides, this deterministic technique applies without change to optimal control synthesis through Pontryagin approach.

"Volterra Filtering" — Classically, Volterra filters are polynomial filters with finite time-horizon FIR). Note that the well-known Kalman filter doesn't belong to that class. An infinite time-horizon (IIR) version of Volterra filter has been developed and allows economical non-linear solutions, which are well-suited for embedded systems. When constrained to finite dimensional realizations (separable kernel),

the optimal parameters may be computed without any approximations for bilinear stochastic systems. This generic class can achieve effective approximations of most SNL encountered in practice.

"Hereditary Identification" — The group has also developed original techniques for the optimal identification of stochastic (or not) dynamical systems, based on hereditary algorithms (linearly increasing memory, with respect to data length). Being essential to exact resolution, such an hereditary memory happens to be crucial for critical applications (e.g. modal proximity), and provides easily for adequate truncating, as a function of criticity. First developed for ARMAX signals under the form of lattices, it has been recently extended to homogeneous bilinear systems realization and identification [ACTI380] [ACTI399]. In that last case, it has been shown that system realization leads to a multi-hereditary algorithm. Besides, new canonical forms for bilinear homogeneous dynamic systems have been derived. This identification approach has been applied to the human locomotion modeling using motion capture (collaboration with the LAAS Gepetto team) [ACTI572].

"**Diffusive representation"** — Diffusive representation is a new operator theory devoted to general dynamic problems. It was introduced and developed at LAAS during the last ten years. Its main interest lies in analysis, approximation and synthesis of dynamic operators of pseudodifferential nature. Diffusive formulations are well adapted to various situations encountered in many current problems of physics, control or signal, namely when the underlying complexity is excessive for standard formulations, due in particular to hereditary dynamic behaviours intimately associated with pseudodifferential components, often of long memory type [ACL461]. In the framework of diffusive representation, such major shortcomings are by-passed by use of suitable state realizations especially devoted to this purpose, and whose numerical approximations are straightforward.

Highlights and Major Achievements

The group has a long-track of research publications in top-notch journals and conferences like: IEEE Infocom, Queueing Systems, Performance Evaluation, Journal of Applied Probability, IEEE Transactions on Automatic Control, IEEE Transactions on Communications, IEEE Transactions on Signal Processing etc.

The PhD student Joan Solà have received the second prize of the GDR Robotique "2007 Best Thesis in Robotics Award".

Two staff members are also co-founders of QoS Design. QoS DESIGN is a spin-off company of LAAS working on innovative solutions in the areas of performance evaluation, simulation techniques, design and planning of telecommunication networks.

Significant projects and collaborations

Participation in projects (both at the national and international scale) and collaborating with academic partners worldwide are a priority at the group. In this respect, the group members have established very close collaborations with researchers from INRIA, CWI (National center for Mathematics and Computer Science in the Netherlands), EURANDOM (Eindhoven, the Netherlands), CREATE-NET (Trento, Italy), California Institute of Technology (US), Bell-Labs (US), University of California at Berkeley (US), Helsinki University of Technology (Finland) the University of Liverpool (UK), and the Université Libre de Bruxelles among others. In addition we also have long lasting collaborations with several industrial partners like SFR, Index Multimedia, AIRBUS, FT R&D, Alcatel, Thales, DCNS, NavoCap, and QoS Design.

As a consequence, our research activities are exploited within several cooperative projects. They are all based on partnerships with industry, large groups or SMEs:

- ARSys: deterministic particle filtering for RADAR acquisition and tracking in critical situations to conventional treatment. Validation on actual ARMOR Radar System data.
- AVIPS project: new algorithm for the automatic generation of traffic matrices from user activity description.
- BINAUR project: System travel assistance for blind students in urban areas. Modeling and identification of the human locomotion for estimating the position of a pedestrian. Fusion inertial sensors and GPS.
- ECODE. European project (INFSO-ICT-223936) of the European Seventh Framework Programme (FP7) that aims at developing an experimental cognitive distributed engine. Other members include Alcatel, INRIA, Univ. College London, Univ of Lancaster and Univ. of Liege.
- EGNOS-BUS project: development of an efficient algorithm that disallows GPS multipath whose case is represented by a Poisson process.
- LNE. Modeling identification and control of MEMS for voltage references in metrology. Convention 2008-2009, Programme Métrologie, Laboratoire National de métrologie et d'Essai (LNE).
- SMALLCELL
- French-Netherlands Scientific Cooperation "Van Gogh" (Ref: PHC 20457QC) on Transient and asymptotic analysis of TCP, 2009-2010.
- French-British Scientific Cooperation "Alliance" (Ref: PHC 18246WF) on Optimal control of delayed systems, 2008-2009.

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Methods and Algorithms in Control – MAC –

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Long term visitors: N. Aouani, F. Bugarin, C. Olalla Martinez, L. Rodrigues

Objectives and positioning

The activities of the group are centered on the field of Automatic Control and System Theory, with a focus on feedback control structure: Closed-loop control versus open-loop control strategies, even if some side results have also been obtained in an open-loop setup, on specific optimal control problems.

In particular, MAC is interested in modeling, analyzing and designing control systems that meet heterogeneous performance and stability requirements for complex systems possibly affected by information restrictions. In every case, the members of the group share a common objective: Exhibit constructive theoretical conditions characterizing solutions to various control problems while providing effective efficient numerical algorithms based on optimization theory. The main tool allowing building a unified methodology is the Lyapunov theory which is central to the results produced by MAC group members. It mainly amounts at looking for certificates of stability and performance (Lyapunov functions) for analysis and control system synthesis purposes.

Completing this theoretical frame, the evaluation of our results on applicative issues represents an indispensable brick to the contribution of the group. Various application domains have been considered hitherto with a particular effort on the aeronautical and space fields, taking advantage of the local context of Toulouse and its dedicated networks and structures: RTRA STAE, Aerospace Valley (Pôle de Compétitivité AESE) and the joint laboratory AIRSYS (Airbus, IRIT, LAAS, ONERA).

This general picture is explicitly detailed and illustrated in the sequel.

When designing and analyzing some control system for highly demanding applications (space-borne control systems for instance), guaranteeing internal stability of the closed-loop system in an uncertain environment generating possible complex phenomena (parametric uncertainties, unmodelled dynamics, isolated nonlinearities…) is one of the fundamental issue to be tackled by the designer. Lyapunov theory is therefore a natural tool for obtaining various stability tests in different contexts (robust stability tests, identification of local stability domains for nonlinear systems…). Traditionally, MAC has extensively used Lyapunov theory and related tools in the past decade. Recent developments have mainly consisted in looking for more sophisticated parameterization of Lyapunov certificates while keeping in mind tractability of associated numerical tests.

For robustness analysis purpose, fractional quadratic parameter-dependent Lyapunov functions allow to generate less conservative robust stability and performance (H_2, H_∞ or impulse-to-peak) conditions that may be checked using the Linear Matrix Inequality (LMI) formalism. This framework may be easily extended to the case of discrete-time periodic uncertain systems by considering parameter-dependent periodic Lyapunov functions. In the same spirit, associated with LaSalle principle, piecewise quadratic Lyapunov functions are employed to determine stability domains of systems with nonlinear elements. Identically, Lyapunov-Krasovskii functionals are determined for the case of systems with time-delays. Last, infinite dimensional Lyapunov functions are built for systems described by Partial Differential Equations (PDEs).

From a synthesis point of view, Lyapunov theory may also be employed for various control laws design (complete or partial information) for linear and nonlinear systems. For instance, in this last case, using a backwards procedure, the controller is derived for a given choice of Lyapunov function. In this context, either continuous and/or hybrid control systems (discrete-continuous dynamics) are constructed from the Lyapunov certificate.

In addition to internal stability, passivity and small-gain properties as particular instances of a more general dissipativity theoretical framework may also be studied. New sector conditions are defined and Lur'e functionals combining nonlinearity and parametric uncertainty dependence are looked for. These last results find a natural extension in the topological (quadratic) separation framework that

allows unifying in some way Lyapunov internal approach and input-ouput viewpoint. As demonstrated on robustness problems including parametric uncertainties and/or time-delays in the loop, topological separation gives new possibilities to handle more complicated parameter-dependence of the Lyapunov certificate by considering an extended formulation of the problem in a descriptor context. The reduction of conservatism of previous existing results has been demonstrated on a space industrial benchmark (robust analysis of ACS of Demeter).

The constructive numerical algorithms produced by the group mainly rely on efficient convex optimization tools as the Semi-Definite Programming (SDP) with its associated LMI formalism. In general, the way chosen to tackle a particular control problem is to recast it as a convex optimization problem involving Lyapunov matrices, controller matrices and possible slack matrix variables as decision variables. For such problems that cannot have direct convex LMI formulations, some new heuristics (mainly of descent-coordinate type) exploiting problem structure have been produced. This is the case for instance for the problem of stabilization via static output feedback or for some fixed-order anti-windup compensator design. An important point that should be stressed is that optimization theory is not only used to get efficient numerical tools but also as a field producing new powerful ideas for control purpose. This optimization-oriented viewpoint is indeed at the origin of new theoretical contributions. As a matter of fact, the so-called "slack variables" technique (also known as dilated LMIs conditions) is nothing but a reformulation of the Lagrangian duality allowing getting sufficient conditions formulated as convex relaxations of the original problem. Reciprocally, these strong relationships between optimization theory and control theory have lead original results on the Generalized Problem of Moments (GPM). GPM is an infinite-dimensional linear optimization problem on a convex set of measures, intractable numerically in its full generality. On the other hand, if the support of the measures is contained in a compact basic semi-algebraic set (defined by polynomial inequalities), and the functions involved are polynomials, then one can define a numerical scheme based on a hierarchy of LMIs, which provides a monotone non-decreasing sequence of lower bounds that converges to the optimal value of the GPM; sometimes finite convergence may even occur.

In all these fundamental research areas, the group has visible position at the national and international levels. Following the precursor works on robust control in the eighties, the group has always kept a central position on the subject, being able to promote new ideas and research directions, most often in collaboration with the main teams on the subject in the world (UNICAMP-Brasil, Berkeley, New-York University, UCLA…). Such an observation is also true in the framework of isolated nonlinear elements in control, where the main teams in the world (with whom we generally collaborate) are the University of Leicester, ETH Zurich, Berkeley, University of Washington, Virginia University… This leadership position is illustrated through co-signed papers, co-edition of books [LNCIS, vol.308, 2005], [LNCIS, vol.312, 2005], [LNCIS, vol.346, 2007], [LNCIS, vol.357, 2007], or co-edition of special journal issues or sections [European Journal of Control, 12(1), 2006], [Biotechnology progress, 25(3), 2009], [IEEE Transactions on Automatic Control, 54(5), 2009], organization of manifestations (in particular the IFAC-ROCOND Symposium in 2006), and numerous visitors and invitations for talks. Members of the group are currently (or have been during the last four years) associate editors of international journals among the most recognized (Automatica, IEEE Trans. on Automatic Control, Int. J. Robust and Nonlinear Control, IET Control Theory and Applications, European J. of Control, Electronic J. Math. Phys. Sciences, SIAM J. on Optimization, IMA J. of Mathematical Control and Information, J. of Franklin Institute, RAIRO Operation research…) and S. Tarbouriech is editor in chief of J. Européen des Systèmes Automatisés. The recognition of the group in optimization has been strongly improving in the decade, in particular thanks to original works on “polynomial optimization” and associated software developments. In addition to an active position in the optimization and algebraic geometry community (IMA Minneapolis, Berkeley, Caltech, ETH Zurich), the approaches developed in the group have found a great interest in other communities (vision, signal processing…).

Highlights and Major Achievements

As mentioned in the previous paragraph, the main robust analysis results are now developed in the general setup defined by the topological or quadratic separation [Peaucelle et al. 2007 – ACL304]. This concept provides a theoretical framework that unifies tools and notions related to internal stability and Lyapunov theory with those from the input-output viewpoint. Moreover, robustness conditions for a large variety of uncertainties and/or time-delay operators (static, time-varying…) may be derived for a wide variety of performances. In particular, the descriptor formulation of these new robustness conditions allows drastic improvement the trade-off between the numerical complexity of the tests and the reduction of their conservatism.

On the complex problem of the multi-objective control via structured control systems, different suboptimal solutions approximating the genuine optimal solution via more or less conservative convex relaxations and adequate heuristics may be easily built using usual SDP numerical tools. The robust analysis and multi-objective control functionalities build up the basis of a new dedicated toolbox named RoMulOC (figure 1) [Peaucelle, Arzelier 2006 – ACTI1577].

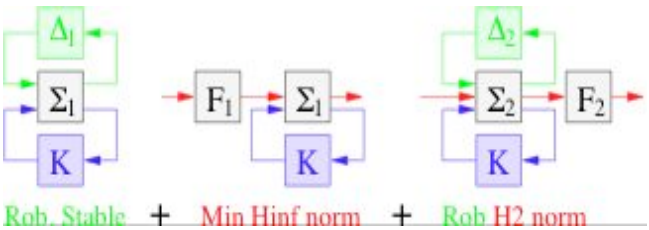

Figure 1: Robust Multi-Objective Control toolbox

Moreover, these results provide promising directions for application to launchers [Arzelier et al. 2006 – ACL124] and aerospace systems for the autonomous formation flight [Theron et al. 2007 – ACTI1861], involving linear periodic models [Farges et al. 2007 – ACL276]. Collaborations with the French Space Agency (CNES) as well as industrial actors of the space domain (Astrium, Thales-Alenia-Space) have been recently reinforced on issues ranging from the robust control of the interferometric cartwheel formation (figure 2) to the robust guidance for the rendezvous problem in elliptic orbit or the anti-windup momentum unloading via magnetic actuators.

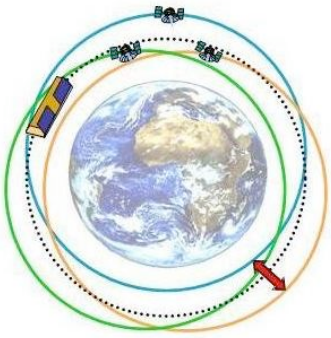

Figure 2: Interferometric cartwheel

Related to the presence of nonlinear elements in the control loop, the anti-windup strategy has been widely studied those last years, allowing new conditions to build reduced order anti-windup controllers [Tarbouriech, Turner 2009 – ACL560]. A fundamental result has been at the origin of such techniques: the modified nonlinear sector conditions which allow encapsulate the isolated nonlinear elements involved in the control loop [Gomes da Silva Jr, Tarbouriech 2005 – ACL4], [Tarbouriech et al. 2006 – ACL203].

Such a strategy has also been employed in the control of the yaw rate of a civil transport aircraft (figure 3) during the ground phase.

Figure 3: On-ground aircraft control. Joint work with ONERA

In this context, a non-standard application of anti-windup control has been used where saturations are not classical elements but are used to represent some nonlinear ground forces (figure 4), which magnitudes highly depend on the runway state (dry, wet or icy) [Roos et al. 2007 – OS39]. This case study illustrates that, recently, in addition to classical saturation functions, a particular focus has been put on other types of nonlinearities, typically arising in sensors and actuators: for example backlashs, dead-zones, mechanical games…

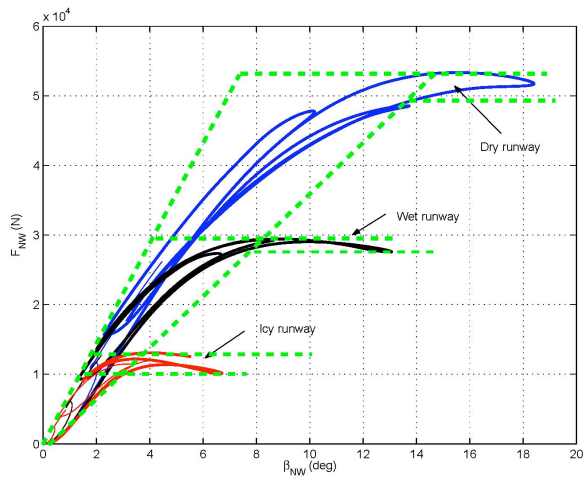

Figure 4: Inclusion in sectors of nonlinear wire-ground interaction for various runaway state

Stability analysis (and control synthesis) conditions have been expressed through LMIs, based on the use of quadratic functionals and generalized sector conditions. New classes of nonlinear systems have begun to be investigated: Hybrid systems [Loquen et al. 2008 – ACTI1411], [Prieur et al. 2007 – ACL371], mixed linear and nonlinear systems [Castelan et al. 2008 – ACL480].

Further, certain classes of nonlinear systems have been investigated, yet using Lyapunov framework, in the context of stabilization [Andrieu, Prieur 2008 – ACTI1410], optimal control of bilinear systems [Baudouin, Salomon 2008 – ACL448], state

observation and output feedback [Andrieu et al. 2008 – ACL454]. Infinite-dimensional robust H∞ control has also been addressed with application to an adaptive optic system described by linear PDEs [Baudouin et al. 2008 – ACL460]. Such new directions may be associated to the arrival of three research assistants (CR) during the last years: C. Prieur (2004), L. Baudouin (2006) and V. Andrieu (2007). We can also mention the study of inverse problems, duals of controllability problem, since the point is to determine parameters of a PDE from measurement of the solution [Baudouin, Mercado 2008 – ACL391]. For nonlinear systems, optimal control theory has also been an important mean for the design of robust nearly-optimal stabilizing control laws through their connections to hybrid systems or to moments approach, for the numerical computation of optimal controller via occupation measures.
Moreover, regarding linear time-varying systems, necessary and sufficient conditions based on differential Lyapunov equations have emerged allowing to characterize both the envelope capturing the closed-loop trajectories and the time-varying controller [Garcia et al. 2009 – ACL576]. Time-varying control is also concerned when dealing with robust adaptive control, which is an emerging subject issued from a PICS collaboration with Russia [Peaucelle, Fradkov 2008 – ACL518].

The research activities of the group on the Generalized Problem of Moments (GPM) may be interpreted, in the process control framework, as a dual approach of Lyapunov one. The notion of occupation measure (manipulated through moments), is central in Markov process theory and ergodic dynamical processes, but has not been very often considered in linear, nonlinear or robust control. The evaluation of a stability and performance certificate through a Lyapunov function may be however reinterpreted as the dual problem of occupation measures search of which moments are linearly constrained [Lasserre et al. 2008 – ACL508], in a context of optimal control for polynomial systems. GloptiPoly 3 software may then be used for a constructive determination of such occupation measures, by solving the GPM via LMIs [Lasserre et al. 2008 – ACL456]. Polynomial LMI approach has also been exploited in the design of uncertain 2-1 sigma-delta modulators used in telecommunication [Kernan et al. 2008 – ACL395], and in vision [Kahl, Henrion 2007 – ACL322]. Several other applications of the theory of moments in dynamical systems as well as in other areas (notably for solving polynomial equations) have been developed [Lasserre 2008 – ACL509]. The 2009 Lagrange prize on continuous optimization by the Mathematical Programming Society and SIAM obtained by J. Lasserre for the seminal paper related to sum of squares [Lasserre, 2006 – ACL261] awards the novelty and relevance of these theoretical results.

Significant projects and collaborations

A majority of the research activities of the MAC group are often carried out in collaboration with academic or industrial partners, in an international context.

Numerous "pure" scientific collaborations enrich the fundamental research of the group, through exchanges of permanent staffs, from a few days to a few weeks. This is made visible by the list of our external co-authors during the examination period (2/3 of our journal papers are co-signed with people from other institutions). Collaborations also involve student exchange programs (PhD student in "co-tutelle", reception external PhD students for a few weeks to a few months, visit of our PhD students for a few weeks in foreign research teams). In particular the collaborations with UNICAMP (Campinas, Brazil), UFSC (Florianopolis, Brazil) and UFRGS (Porto-Alegre, Brazil), supported by a STIC-Amsud program, a CAPES-COFECUB program and soon a LIA (whose French head will be Hisham Abou-Kandil); the collaboration with the Czech Technical University (Prague, Czech Republic), supported by bilateral programs (D. Henrion is associated member of the Faculty of Electrical Engineering); the collaboration with the Polytechnic Faculty of Mons (FPMs, Belgium) which favored exchange of PhD and ERASMUS students.

Another interest of such collaborations is that, although the research activities of the group mainly focus on theoretical aspects, they are fed with applications issued from experimental devices provided by our colleagues. An effort in this direction has been produced in the last few years. For instance, here is a non exhaustive list of external collaborations:

- Collaboration with ISAE: A clamped-free-free-free plate together with a horizontal cylinder with liquid mimics, at low frequency, a real plane wing filled with fuel;
- Collaboration with LIRMM: The ANR project Objectif100G concerns the robust control of a high speed manipulator subject to vibrations;
- Initiating collaboration (STIC-Amsud program) with the Mechanical Engineering Faculty of UNICAMP (Campinas, Brazil) regarding the control of flexible structures;
- Collaboration with LISBP: To bridge the gap between classical control theory and numerous modeling, analysis, observation control problems in biochemical and biological field [Queinnec, Spérandio 2005 – ACL65];

- Collaboration with URV (Tarragona, Spain): Evaluate robust control strategies on converters;

as well as a list of internal collaborations (with other teams of the lab):

- Pole RIA: The problem of positioning a 3-DOF camera with respect to a mobile visual target has been addressed in a joint PhD;
- Group ISGE: It has been at the origin of our collaboration with URV (Tarragona, Spain), and proposes some challenging problems for the control of photovoltaic devices [Leyva-Grasa et al. 2006 – ACL126];
- Group OLC: It concerns control problems involving time-delay [Labit et al. 2007 – ACTI1035], in particular AQM congestion control, of TCP/IP networks and should benefit from the LaasNetExp platform.

All these experimental devices are completed by our "helicopter" plateform, which is itself an interesting source of collaborations [Fradkov et al. 2009 – ACL544].

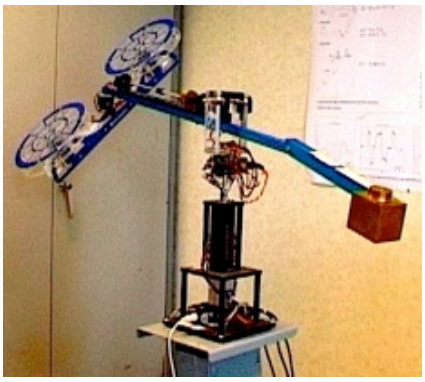

Figure 5: Helicopter platform

Besides those academic collaborations, industrial partnerships have increased during last period, in particular in the domain of aerospace control systems. MAC has been involved for many years in the group for Aeronautical Research and Technology in Europe (GARTEUR, from the period of AG08 twelve years ago to AG17 which has recently received the Garteur Best action group award). Some members have been part of the AG15 (Pilot-in-the-loop oscillations (PIO) - Analysis and test techniques for their prevention, Phase 2, 2004-2006) and AG17 (Nonlinear analysis and synthesis techniques in aircraft control) programs. Even if such programs are not financially supported, they nevertheless strongly contribute to increase our visibility in the European aeronautic scientific and industrial community.

CNES (French Aerospace Agency) is a solid partner of the group. During the last four years, several R&T actions took place with the DCT/SB/PS (AOCS) service:

- A R&T action has been initiated at the beginning of 2007 (until November 2009) which addresses the problem of interferometric cartwheel formation robust control;
- A R&T action (10/2008- 05/2009) concerns the improvement of robustness and ACS validation using LFT modelling and quadratic separation based robust analysis;
- A PhD student (10/2006-) is currently supported by a CNES and Thales Alenia Space grant. He is working on anti-windup momentum unloading via magnetic actuators.
- A R&T action (12/2007- 12/2009) on the design of robust guidance schemes for the Rendezvous problem in elliptic orbits is presently in progress. Original techniques based on algebraic geometry and polynomial optimization backgrounds have already given promising results.

This strong link with the CNES has also given rise to the four months visit of D. Arzelier in the DCT/SB/PS (AOCS) service, for the development of generically uncertain LFT models for flexible satellites in the context of the Demeter benchmark. All these aspects will be yet favored by the arrival of a young assistant professor (MCU), C. Louembet (2008), specialist of optimal control and space applications.

This list of collaborations and projects is far from being exhaustive. SNECMA has also be an important partner of the group during the last 6 years, with 2 PhD related to advanced robust control of a turbofan engine. We have been or are also involved in 5 ANR projects (MOGA, SICOMAF, Objectif100G, ArHyCo, PROSSDAG), some of them being pure academic research while others are conducted in collaboration with industrial partners.

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

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Non Permanent Staff:
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PhD students: M. Ayala, F. Baniel, A. Ben Hmida, B. Gacias, H. Gharbi, F. Gueye, W. Karoui, O. Koné, S. Lannez, S. Ourari.

Objectives and positioning

With the advent of information technology, a research on systems of activities is more than ever a great challenge that impacts the society and the environment. In this context, the research work of the MOGISA group focuses on studying systems in which discrete activities must be executed. Execution of these activities is subject to constraints related to the use and availability of resources, and their integration into projects or processes.
In particular, the main research topics are on task assignment and scheduling, transportation systems, supplying and production planning. The associated problems under consideration may be limited to a unique decision centre, or may be broadened to a global supply chain integrating a network of partners.
These research topics are applied to project management, computer systems (process execution on parallel processors), manufacturing (workshops, supply chains), and services (transportation, telecommunications, health, environment). One common characteristic of most of these domains is their socio-technical entanglement, with man occupying a central position and a variety of roles.
The strength of the group is its ability to develop original and interdisciplinary approaches, notably based on the concepts of flexibility and robustness.
The objective is to define generic models, efficient methods, and reusable tools providing supports to analyze, design, and pilot systems of activities in an uncertain, disturbed, and highly dynamic environment. Such requirements are achieved using techniques from operations research: integer programming (IP), graph theory, tree-search methods, metaheuristics; or from artificial intelligence: constraint propagation.

Skills and positioning

Our skills are mainly in the proposition of optimisation algorithms for the supply chain management (SCM) and the resolution of production planning and scheduling problems. Since a few years our research work is currently inflecting towards the topic of transportation, more precisely on multimodal and multiobjective vehicle routing problems, and the consideration of environmental constraints and criteria.
Managing systems of activities require a cross-interaction with scientific communities. On the one hand, it involves works in industrial engineering (IE) for SCM or production research: IFAC, I^4e^2, GDR MACS, Club GI... On the other hand, it concerns operations research (OR) and artificial intelligence (AI) for combinatorial optimisation or algorithms: EURO, INFORMS, ROADEF, GdR RO…
An important originality of MOGISA group is its participation in all these communities. In scheduling for example, we were among the first to make a convergence between the methods and tools used in OR and AI. Our constraint-based approach for scheduling and decision-aid contributes to bridge the gap between planning in AI and scheduling in OR. Our "constraint-based scheduling" methods are well recognized by other cross-disciplinary (mainly AI-OR) researchers (*e.g.*, S. Smith, Carnegie Mellon Univ.; M. Fox, Univ. of Toronto; P. Baptiste, Ecole Polytechnique; J. Carlier, Univ. de Techn. de Compiègne; E. Néron, PolyTech'Tours; W. Nuijten, P. Laborie, IBM-ILOG). Our resource constraint propagation techniques (*e.g.*, energetic reasoning) are widely spread over the scientific communities and industrial solvers.
A common, recurrent research object for more than a decade is the development of methodologies able to offer flexible solutions satisfying robustness requirements. In this context, the group has a visible position at the national and international levels concerning the topic of hierarchical planning by aggregation/disaggregation, as well as the application of robust control to production and inventory management. In particular, results of our group have influenced other teams from the LAPS (Bordeaux) or the CRAN (Nancy). In this topic, the group also greatly participated to the regional federative structure IODE ("Ingénierie des Organisations DistribuéEs") with members from ONERA, LAPS, LGP-ENI of Tarbes, CGI-EMAC (Albi), LATTIS-INSAT… The group also participated in the IFAC Technical Committee on "Manufacturing, Management and Control" and in the European Coordination Action "CODESNET" (with

Politecnico di Torino, Italy; University of Nottingham, England; Linköpings Universitet, Sweden). Furthermore, the research results of the group on robust scheduling are recognized by main personalities in the topic (*e.g.*, W. Herroelen, Katholieke Universiteit Leuven, Belgium) and have been used in various labs in France (LORIA, Nancy; the computer science labs of Tours and Avignon).

Models and methods

We investigate mathematical models and methods for discrete optimisation (DO) and constraint satisfaction problems (CSP). Our achievements in DO and CSP are twofold. First, we aim at proposing general exact or approximate solving methods often lying on the integration of hybrid components from OR and AI. More particularly, we concentrate on tree search procedures associated with learning techniques, metaheuristics, large neighbourhood search, column generation, and branch-and-cut techniques. We also tend to integrate dynamic and uncertain aspects in general-purpose methods to deal with the cases the problem to be solved evolves over time. Our work on modelling and control of dynamic discrete-event systems via the (max,+) theory falls into this category.
Secondly, we study the complexity of specific problems and we propose solving methods adapted to their structure and dynamics. We focus mainly on problems issued from SCM such as scheduling and vehicle routing problems, as explained below.

Classes of problems

In the SCM area, we focus on the planning process of an entity within a chain and suggest an approach aiming at improving the coordination between supply chain's partners (customers, suppliers, subcontractors). A special attention is devoted to the modelling of temporal features that are associated to the different elements of the studied system (cycle times in the production, delivery delays of suppliers, periodic updating of data).
In scheduling, a first work deals with the design of new models and algorithms, either to improve the state-of-the-art results of known NP-hard scheduling problems, or to solve new problems with complex constraints issued from real applications. The problems under study integrate some of the following constraints: cumulative resources, setup times, generalized precedence constraints, resource flexibility, cyclic scheduling. We are more particularly concerned with the proposition of new IP formulations, polynomial or exponential neighbourhoods, discrepancy-based tree search procedures, and constraint propagation techniques. Taming uncertainty is the second major issue we addressed for scheduling problems. We focused on reactive methods aiming at taking account of unexpected events with a necessary compromise between solution quality and CPU time.
In transportation, we aim to provide models and methods addressing complex transportation systems. A first class is composed of problems that incorporate real-life constraints that are not always considered in academic problems or not together. An instance is rich vehicle routing problem, which deals with many constraints: time windows, capacity constraints, and economic constraints... Another context considered is dynamic environment where no everything data is set in stone and solutions able to cope with parameters unknown a priori have to be found. The study of multiobjective vehicle routing problems is also a speciality of the team. The goals here are to enrich the considered problems by taking into account several conflicting objectives. A last point concerning transportation systems is the proposition of shortest path algorithms for multimodal time-dependent systems. Both heuristics and exact method are proposed. The first allows addressing real-life problems while the later is a way to validate our heuristics.

Highlights and Major Achievements

During the considered period, we published our work in highly ranked OR, AI, and IE international journals (*Annals of OR*, *European Journal of OR*, *Computers and OR*, *INFORMS Journal on Computing*, *Journal of Scheduling*, *Journal of Heuristics*, *Computers and IE*, *Engineering Applications of AI*, *European Journal of IE*, *International Journal of Production Research*, *International Journal of Production Economics*, *Journal of Intelligent Manufacturing*, *International Journal of Systems Science*…) and conferences (*CPAIOR*, *IEEE-CDC-ECC*, *AIAA-SDM*, *CDM*, *MISTA*, *PATAT*, *ICSSSM*, *INCOM*, *PMS*, *MAPSP*, *MIC*, *IESM*, *MOSIM*, *CIFA*, *ROADEF*…). We are involved in collaborations with several national and international teams, as well as in an ANR "blanc" project, which underlines the possible breakthrough of our ongoing work. We had also several industrial contracts showing the applicability of our research.
The major results are presented in the sequel following four major topics in accordance with the two sides of our research activities: Discrete optimisation and constraint satisfaction; Supply chain management; Scheduling; Transportation. Furthermore, we also present the main research collaborations, dissemination and administration activities of some members of our group.

Discrete optimisation and constraint satisfaction

We obtained several results for the improvement of general-purpose discrete optimisation methods through the integration of OR and AI techniques. We showed how constraint propagation could be instrumented to compute tighter cutting planes for IP relaxations [Demassey *et al.*, 2005]. We proposed new large neighbourhood search (LNS) methods, where the neighbourhood exploration lies in solving through implicit enumeration an NP-hard subproblem. We proposed in [ACL611] an LNS based on dynamic programming, and in [ACL447] an LNS based on IP which obtained the best average results on hard frequency allocation problems. This method has been successfully applied to real problems in the context of a contract with Thales Alenia Space.

New tree search procedures based on discrepancy search are proposed, as well as some learning on impact of decision-making during search. For Constraint Satisfaction Problems (CSPs), the proposed method, named YIELDS (Yet ImprovEd Limited Discrepancy Search) produced the best results on some randomly generated instances [ACTI25, ACTI731]. The method has also been successfully experimented on job-shop and Latin square instances [ACTI731].

For the integration of dynamic aspects in combinatorial optimisation, we proposed a general framework applied to the dynamic frequency allocation problem, alternating constructive and repairing phases [ACL595].

We developed a control law that minimizes the delay of a discrete-event system while taking into account constraints on the system such as resource capacity, resource availability, and processing times [Houssin *et al.*, 2006] and a control law that optimises the just-in-time criterion for discrete-event dynamic systems [Houssin *et al.*, 2007].

We also have studied metaheuristics for multiobjective problems. First, we have proposed diversification mechanisms for multiobjective evolutionary algorithms and studied the use of parallelism to improve the quality of the search. We also have proposed a paradigm, called TAPaS, to apply single solution methods like Tabu search heuristic to multiobjective problems [Jozefowiez *et al.*, 2007b]. Another topic of research in the field of methods for multiobjective problems is the design of cooperative methods: multiobjective evolutionary algorithms with Tabu search heuristics [Jozefowiez *et al.*, 2007b], metaheuristics with exact methods [Jozefowiez *et al.*, 2007a], and metaheuristics with specific heuristics [ACTI1358].

Supply chain management

In a first study of this axis, different management modes have been modelled: distributed, centralized, and hybrid structures. A simulation tool relying on commercial optimisation software has been developed in order to assess the properties (robustness and reactivity) related to the proposed approaches when unforeseen events occur and modify data (demand, material supply, etc.).

The second study focuses on the planning process of an entity within a chain and suggests an approach aiming at improving the coordination between supply chain's partners (customers, suppliers, subcontractors; see Fig. 1).

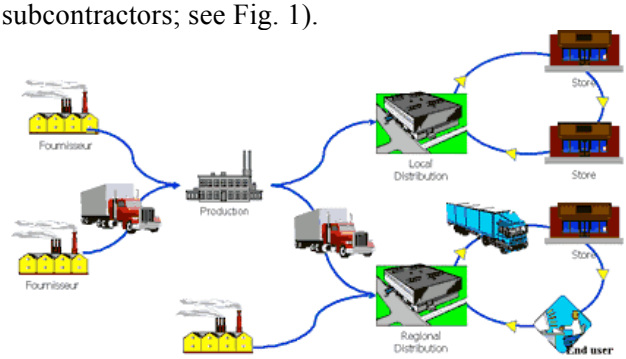

Figure 1: Supply chain management

A special attention is devoted to the modelling of temporal features that are associated to the different elements of the studied system (cycle times in the production, delivery delays of suppliers, periodic updating of data). A dynamic planning process and a simulation tool are proposed in order to manage firm and flexible demands [ACL402, ACL552].

The robustness concept is the central issue of a third work based on a two-level decisional structure. Temporal aggregation mechanisms are used at the upper level in order to determine a mid-term plan, robust towards features unknown at this level. A "guiding" plan is then derived from this aggregate plan and transmitted to the lower level which deals with short term decisions; a dynamic disaggregation is then performed which enables to react to uncertainties and disturbances [ACTI1077].

Another original approach relying on queuing theory and on game theory investigates two important issues in an uncertain context: the definition of supplying policies when different suppliers have uncertain delivery delays and the definition of optimal contract-based policies between adjacent entities within a supply chain [ACL257, ACL378, ACL446].

Scheduling

We brought an important contribution for solving NP-hard scheduling problems, and in particular, extensions to realistic constraints of the standard job-shop problem. We proposed new list scheduling algorithms [ACL79] and a branch-and-bound method

embedding new dynamic programming and constraint propagation algorithms [ACL411] for the job-shop problem with setup times, significantly improving the best results from the literature. For the integrated employee and job-shop scheduling problem, we proposed a mixed constraint and IP decomposition approach [ACTI501].

We edited a book gathering our experience in production scheduling [DO14]. In this context, we develop a specific discrepancy-based method called CDDS (Climbing Depth-bounded Discrepancy Search). It obtained the best existing results for hybrid flow-shops [ACL337, ACTI617]. It also provided promising results on flexible job-shops [ACTI890, ACTI1099].

For the resource-constrained project scheduling problem (RCPSP), the best known lower bounds have been improved with an hybrid cutting plane method [Demassey *et al.*, 2005] and a new *any-order* schedule generation scheme (SGS) has been proposed that permits to build up in polynomial time efficient resource feasible schedules using various priority rules [ACTI47]. The problem of inserting an activity in an existing schedule for an RCPSP with minimum and maximum time lags, fundamental for both reactive scheduling and neighbourhood search, is tackled in [Artigues and Briand, 2009] and proved to be NP-hard. We edited a book gathering our experience on the RCPSP together with the works of well-known research teams [DO13].

Another important research axis concerns the study of analytical and numerical dominance conditions of optimality for the single-machine scheduling problem (SMSP). The interest of this study was twofold. First, it led to an original and powerful IP formulation that permits to solve SMSP instances having several thousands of jobs [Briand *et al.,* 2009] and that can be adapted to tackle various objective functions (maximum lateness, number of late jobs). Second, the proposed dominance conditions have been used for characterizing a robust set of dominant schedules having a known worst performance and a known cardinality, which can be computed in polynomial time [ACL315]. For more complex scheduling problems, we established sufficient condition of optimality for characterizing a large set of optimal schedules in polynomial time for the 2-machine flow-shop problem [ACL159], for the flow-shop problem [ACL609] and the job-shop problem [ACL79].

For shop environments, we also study cooperative scheduling approaches [ACL113]. It is assumed that the global schedule is built up by successive negotiations between resources, each resource managing its own local robust schedule, characterizing its own set of dominant schedules. Intending to reach a relevant trade-off between the local resource objectives and a global objective, we analyzed the resource negotiation problem and proposed several cooperation mechanisms [ACTI1227]. To integrate robustness and cooperation for scheduling problems, an ANR "blanc" project was launched in 2009.

A last work arises when studying practical industrial cases. For activity scheduling for make-to-order production of goods (see Fig. 2), we propose a two-level approach [ACL13].

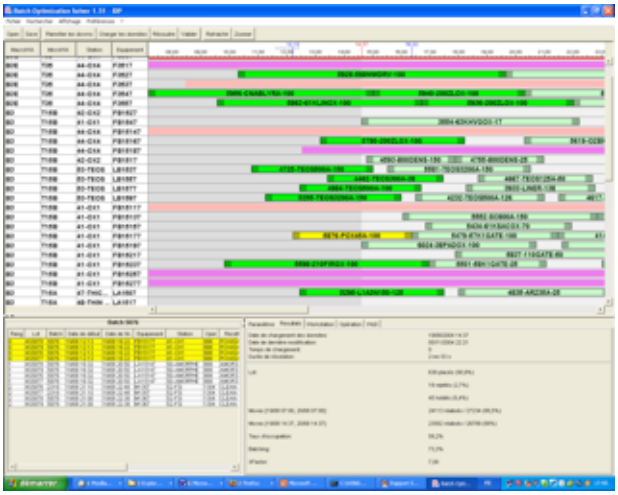

Figure 2: The ORDO® scheduling software

The upper level is in charge of building a coarse-grained schedule (macro-schedule) to optimise the mid-term management strategy of the enterprise whilst the lower level produces fine-grained schedules over a short-term horizon satisfying the macro-schedule and all the production constraints [ACTI827, ACTI1465].

In the context of the collaboration with Airbus France and EADS-CRC, we have studied a design activities scheduling problem that occurs during the development of a new aircraft. We have introduced the original concept of Energy-Precedence-Constraint that enables to state a partial precedence constraint between two engineering activities [ACTI494]. This energy models the minimal work necessary to elaborate design preliminary information that another activity mandatory needs in order to start.

In collaboration with ST-Microelectronics, we proposed new approaches to solve instructions scheduling problems on Very Large Instruction Word processor architectures as cyclic RCPSPs [OS50].

Transportation

In transportation research, our research activities deals with three main formal problems: shortest path problems, dial-a-ride problem, and multiobjective problems. On a more practical side, three main applications are considered: multimodal transportation, waste collecting on-demand passenger transport, and multimodal routes. We studied the dynamic aspects of waste collection linked either to a

weekly collect or to variations of waste quantities, or to insertions of new collecting points. To limit the disruptions occurred in presence of new information, we defined various stability criterion and we proposed several heuristic methods extending standard vehicle routing algorithms [ACTI1110, ACTI1462].

We proposed a hybrid evolutionary and constructive method to solve a crew scheduling problem in underground passenger transport [ACL583]. For on-demand transport, we designed column generation and local search methods to solve vehicle routing problems, optimising various quality-of-service criteria on a multigraph representing alternative routes. The proposed algorithms were embedded in a real reservation system in the Doubs Central Area.

For the case of multimodal transportation network, we evaluated several exact methods for computing bi-objective shortest paths (minimizing both the duration and the number of used modes) (see Fig. 3).

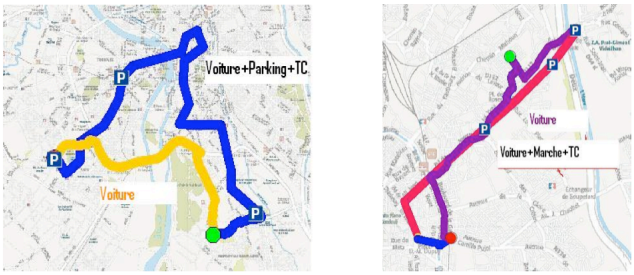

Figure 3: Multimodal transportation network

We have studied the definition and solution of multiobjective vehicle routing problems. In this context, we have proposed a survey and a classification of the literature [Jozefowiez *et al.*, 2008]. Several problems were also proposed and studied several problems. The vehicle routing problem with route balancing [Jozefowiez *et al.*, 2007b] is an extension of the standard capacitated vehicle routing problem but where the length of the tours are balanced in order to guarantee fairness between the drivers. Three other problems were generalization of single objective problems that can be reduced to a single multiobjective problem. Our studies were on the bi-objective covering tour problem [Jozefowiez *et al.*, 2007a], the travelling salesman problem with profits [Jozefowiez *et al.*, 2008] and the ring star problem [ACTI1358]. In the case of the bi-objective covering tour problem, tests were also conducted on real data from the Suhum district in Ghana.

Last, we proposed a new large neighbourhood search method to solve the generalized travelling salesman problem, where the neighbour solution is obtained by finding the best subsequence in a total order of the cities, some being duplicated. Our method obtained the best average results on benchmark instances from the literature [ACL611].

Research dissemination and administration

C. Artigues is co-organizer of the ROADEF (The French OR society) challenge, a well-known international OR competition dedicated to an industrial problem (see for example [ACL408]), and proposed in 2009 by Amadeus that gathered 29 participant teams from 19 nationalities.

In addition, the group aims at consolidating its leadership in Toulouse concerning OR (a regular seminar is proposed and attracts teams from Toulouse Mathematics Institute-Mathematics for Industry and Physics Lab, ONERA-Toulouse Research Centre, INRA-Biometry and Artificial Intelligence Unit, IRIT, ENAC, etc.). It takes a major contribution in the organisation of next ROADEF Conference (see www.roadef2010.fr).

J. Erschler was head until 2007 of the research department at INSA Toulouse and became President of the Cluster for Higher Education and Research "Université de Toulouse" (PRES) until March 2009.

C. Mercé is head from 2008 of the Electrical Engineering and Computer Science department at INSA Toulouse.

Significant projects and collaborations

▪ *PRIME* then *GIMEP: Project of network for multisite integration of energy and production*
Funding: Programme Energie du CNRS (2007-2010)
Partner: LGC

▪ *Exact and approximate algorithms for cyclic project scheduling*
Funding: GdR RO du CNRS (2008-2009)
Partners: LIP6, LINA, ST-Microelectronics

▪ *Decision-aid in waste collecting*
Funding: Région Midi-Pyrénées (2007-2008)
Partners: LGP, CAM, ADEME, Eco-Emballages

▪ *GEDEON: Waste collecting optimised by navigation*
Funding: Région Midi-Pyrénées, Novacom Services (2008-2009)
Partners: LARA-ENAC, CLLE-LTC

▪ *Flight training timetabling*
Funding: AIRBUS (2007)

▪ *Frequency assignment for telecommunications with SDMA technology*
Funding: THALES Alenia Space (2008)
Partner: IRIT

▪ *AVAPRO: Analysis and verification of proactive/reactive approaches in scheduling*
Funding: GdR RO du CNRS (2007-2008)
Partners: ILOG SA, LIMOS Clermont, LI Tours, LAMSADE Paris

▪ *Optimization of inspection vehicles routing on railroads*
Funding: CIFRE – SNCF (2007-2010)
Partner: CIRRELT

▪ *Route planning in multimodal transportation networks*
Funding: CIFRE - MobiGIS (2008-2011)
▪ *SPEED: Management of distributed engineering activities for the integration of complex products*
Funding: EADS CRC (2004-2007)

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Research domain
Robotics and Artificial Intelligence – RIA –

Scientific Topics

The Robotics and Artificial Intelligence (RIA) area conducts research along several themes involving perception, decision-making, motion, action, communication and interaction between the robot and its environment: the other robots, humans and ambient intelligence systems.

Research is conducted by RIA along four strategic streams: aerial and terrestrial field robotics, interactive and cognitive robotics, human and anthropomorphic motion, and algorithms for molecular motion.

These research activities involve also collaborative investigations with research on living systems such as neuroscience, cognitive sciences and biochemistry.

One main feature of robotics research at LAAS concerns the robot itself as an object of study i.e. an artificial entity endowed with integrated sensori-motor and cognitive abilities and acting in an open environment.

The main research themes are:

- Environment perception and modeling,
- Navigation, localization, motion planning and control,
- Natural, artificial and virtual motion
- Manipulation planning and control
- Autonomous decision making, temporal planning, learning
- Control architectures, embedded systems, robustness and fault tolerance
- Human-robot multi-modal and decisional interaction
- Multi-robot cooperation

The Research Groups

The RIA research area is composed of three research groups:

- GEPETTO: Understanding and Modeling Anthropomorphic Systems Motions
- RAP: Robotics, Action and Perception
- RIS: Robotics & InteractionS

This organization has been set up progressively during the year 2006. Previously, RIA was a unique research group. One main argument for the new organization was the will to favor scientific initiative. Indeed, the groups have developed their specifities and their own projects. However, the three groups still maintain and develop a strong synergy between them and contribute in a complementary basis to internal, national or international collaborative projects.

The Main Application Domains

The main application domains considered are: planetary exploration and space, service and personal robotics, embedded systems, PLM, virtual worlds and animation, bioinformatics, neuroscience, transport, driver assistance, defense, surveillance, civil safety

Experimental platforms

The RIA research area benefits from an experimental platform including several indoors and outdoors terrestrial and aerial robots. During the period covering 2005 to 2009, the main equipment consisted essentially of: Rackham, an autonomous interactive mobile robot, Jido, a fully equipped mobile manipulator, HRP-2, a full-size humanoid robot, Dala, a rough terrain mobile robot, and a room equipped with a motion capture system. Several small UAVs have been also developed and used in the recent period.

Several highly qualified engineers and technicians are commissioned by the laboratory to support experimental development, deployment and maintenance of this equipment and the associated software. Activities include also introductory courses to the robot programming and control environment developed at LAAS, as well as maintenance of software tools[1] and particularly robot the software libraries developed by RIA groups.

[1] https://softs.laas.fr/openrobots/wiki

Gepetto

Permanent Staff:
Members: F. Lamiraux (DR), J.P. Laumond (DR), N. Mansard (CR), P. Souères (DR), M. Taïx (MC)

Permanent Staff:
Postdoc: J. Sola
PhD students: S. Dalibard, D. Flavigné, S. Hak, C. Halgand, A. Herdt, O. Kanoun, F. Montecillo, A. Nakhei, N. Perrin, M. Poirier, L. Saab, M. Sreenivasa, M. Tran, A. Truong
Long term visitors: K. Mombaur, M. Morisawa, E. Yoshida

Objectives and positioning

The Gepetto group has been created in 2006. Its research aims at **understanding and modeling the motion of anthropomorphic systems**

Compared to other robotics systems, an anthropomorphic system is characterized by two properties: redundancy and under-actuation. Redundancy because an anthropomorphic body has usually more degrees of freedom (about thirty for the models we study) than the required number of degrees of freedom to accomplish a task. Underactuation because all degrees of freedom are not actuated.

In this context, the goal is to study the computational foundations of the sensory-motor loops of anthropomorphic motion by using techniques from Robotics science. The research activity is structured along three correlated research objects: humanoid robots, virtual mannequins and human beings.

"Motion for humanoid robots" — The goal is to endow humanoid robots with an autonomy of action by using automatic motion planning and execution control systems. This goal is a central theme in robotics science and it is renewed in this context by the complexity of the studied systems. The physical interactions between robots and the environment require that the dynamics of the systems be taken into account, whereas motion planning techniques traditionaly solve these problems by using geometrical and kinematic approaches.

"Motion for virtual mannequins" — The goal is to simulate human being motions inside digital mock-ups and virtual environments. This theme focuses on motion imitation. Here the physical constraints induced by the interaction with a real environment are partially relaxed. This research uses motion capture techniques from which collections of behaviors must be built (in particular for locomotion). On the other hand, it uses robotics techniques for modeling redundant systems.

"Motion for human beings" — The goal is to conduct a multidisciplinary research (robotics and neuroscience) and to explore the sensori-motor basis of human motions. The human body is a highly redundant mechanical system with many degrees of freedom: a goal is to exhibit invariants in different tasks (e.g., locomotion, grasping) and to study their coupling with perception.

Highlights and Major Achievements

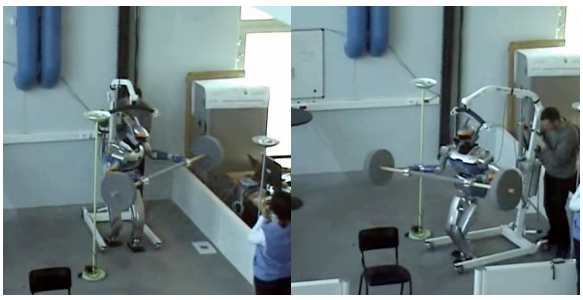
Scientific production of Gepetto over the period:

- 4 book chapters (including a chapter in the prestigious *Handbook of Robotics* recently published by Springer Verlag),
- 20 articles in international journals
- 49 articles in international conferences.

The publications appear in the area of Robotics, Automatic Control, Computer Graphics and more recently Neuroscience and Biomechanics.

In this section we do not develop the various researches which represent the background at the origin of the creation of the group: they deal with probabilistic motion planning (the topic is still active both at the theoretical level and in PLM applications), nonholonomic motion planning for robots with trailers (until 2006), nonlinear control for underactuated systems (e.g. drones), optimal control theory and visual servoing. The selected highlights below cover the core research topic of Gepetto around human and humanoid motion.

"Motion planning and control" — Motion planning and control for humanoid robots constitutes the core research of the French-Japanese collaboration via the JRL lab. The PhD thesis of Claudia Esteves (INPT Leopold Escande 2007 Award) focused on the development of new motion planning algorithms for anthropomorphic structures. The geometry, kinematics and dynamics of the bodies and their environment are explicitly taken into account. This work has been done in the context of research projects conducted between France, Russia and Japan and has been validated by experiments on the HRP-2 robot. Coordination of locomotion tasks and the manipulation of a barbell in a cluttered environment is a break through.

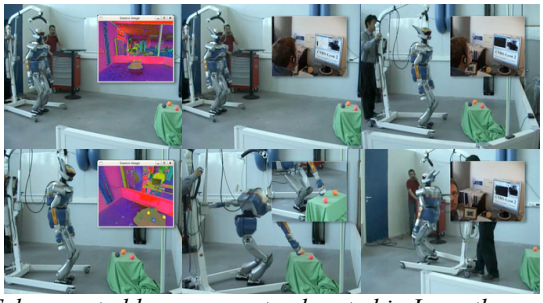


HRP-2 carrying a barbell without falling down [ACL500].

The approach was based on a functional decomposition of the robot [ACL138]. Extension to whole-body motion requires to face both the redundancy and the underactuation of the system at the same time. The solution based on optimization techniques are currently under development (PhD of O. Kanoun, 2009). They already allow HRP-2 to manipulate bulky objects (PhD of M. Poirier, 2009). It is worth noting that the solution makes use of a general motion planning scheme introduced 15 years ago at LAAS in the framework of nonholonomic motion planning. Indeed moving a bulky object by pivoting opens controllability issues that should be carefully modeled to design a general planner in such a context.

Whole-body motion control when manipulating a bulky object [ACTI963].

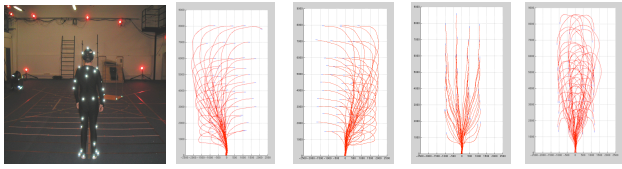
"Software development framework for humanoid robotics" — An important effort is devoted to software development and reuse.



Teleoperated by an operator located in Lyon through natural language interaction, the HRP-2 robot in Toulouse looks for a ball with its vision system and grasps it autonomously [ACTI1005].

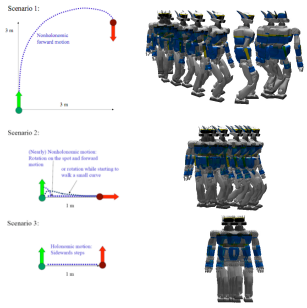
In order to facilitate common development between research teams, a software development kit was developed. HPP (Humanoid Path Planner) allows, in particular, the integration of navigation, motion planning, motion control, manipulation and human-robot communication functions within a common scenario. Such a policy conducts to a good robustness.

"Human locomotion model" — This work was done in collaboration with the neuroscience laboratory (LPPA) of "Collège de France" in Paris. It was inspired by recent work in mobile robotics and optimal control theory for modeling human locomotion in open spaces. As a conclusion, it is proved that the shape of human locomotion trajectories obeys a "minimum jerk" principle (the variation of centrifugal forces is minimized upon orientation changes). This study has been part of the PhD of G. Arechavaleta (2007). It has been published in several international robotics journals [ACL389, ACL474] and, for the first time at LAAS, in a neuroscience journal [ACL372, ACL373]. The work is continued with the PhD of A. Truong.



The basis of the study is a recording of more than 1,500 trajectories performed by six different subjects under a motion capture system.

"Motion understanding via inverse optimal control" — The approach above has been generalized. It is a common assumption that many processes and motions in nature are optimal, but the specific optimisation criterion in a given situation is often unknown.

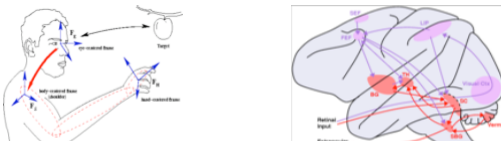


A same model based on optimal control accounts for both nonholonomic and holonomic behaviors [ACTI1394]

We have developed an inverse optimal control approach that can determine the formulation of the underlying optimal control problem from measurement data such as motion capture. It also works if only part of the state and control variables can be observed. The inverse optimal control approach has been successfully applied to study of human locomotion trajectory generation. Such a new line of research appears to be very fruitful both at the level of the new mathematical tools to be developed and at the level of the range of applications.

"Motion imitation via numerical optimization" — We have shown that the imitation of human captured motions by a humanoid robot can be formulated as an optimization problem while the physical limits of the humanoid robot are considered as constraints. The optimization problem is then solved recursively by using an efficient dynamics algorithm, which allows the calculation of the gradient function with respect to the control parameters analytically. The experimental results have pointed out that the imitated motions preserve the salient characteristics of the original human captured motion (PhD of W. Suleiman, 2008, [ACTI1127]). A complementary research in collaboration with Heidelberg Univ. tends to generate human-like motions (e.g. running, diving) by direct application of numerical optimization techniques on dynamic body models.

"Modeling of cortical activity during reaching tasks" — In collaboration with the IRIT laboratory and the neuroscience laboratory CERCO, a study has demonstrated the interest of robotics models in order to describe a visually guided reaching task [OS33]. By using visual servoing models for control, we showed that all the connections between the vision sensor and the grasping body are necessary to compute the Jacobian of the task. These results corroborate some phenomenons recently discovered in electrophysiological recordings of the premotor dorsal cortex of monkeys (thesis of C. Halgand co-advised at LAAS and CERCO).



Different frames participating to a reaching task

"Bio-inspired motor control" — This new line of research tends to transfer the biological models of human motor control to humanoid robots (developed in the framework of the PhD thesis of M. Tran). Preliminary results have been obtained in collaboration with the INSERM-UMPC lab ANIM on reaching tasks (it has been shown on HRP-2 that the model transfer preserves the dynamic of the motion) [ACTI1324]. Another result developed in collaboration with the CNRS-UPMC lab ISIR shows that visual-servoing tends to improve the control robustness with respect to other body-centered controls.

"People and equipment highlights" — In terms of researchers, Gepetto has benefited from the active collaboration with AIST. The presence of E. Yoshida for 4 years has been a real success. He helped a lot to promote humanoid robotics at LAAS and to teach Gepetto team on the HRP-2 platform.

The venue of K. Mombaur as visiting researcher is representative of an evolution of the research performed in Gepetto. At its creation Gepetto skills was mainly based on algorithms and control. Rapidly the study of human motion shown the need to complete the culture of Gepetto researchers with numerical optimization and applied mathematics. The presence of K. Mombaur is a proof of the attractiveness of the group.

In 2008 N. Mansard joined the group as CR CNRS after a postdoc in Stanford University and AIST. Gepetto clearly benefits from his dynamisms and his skills in sensori-motor robot control.

During the period both P. Souères and F. Lamiraux have been promoted as DR CNRS. Gepetto benefits from this recognition.

In terms of material, Gepetto has contributed to the acquisition of a motion capture system that benefits to several research groups at LAAS.

The LAAS motion capture system (10 cameras)

"Special highlight" — The performance realized at SERI 2008 (Paris) on the Carnot Institutes booth deserves to be mentioned. During 3 days the Gepetto team has managed 45 demonstrations on the HRP-2 plateforms in front of a large public. Such a performance demonstrates the robustness of the integration of software tools which are developed within the group.

45 public demonstrations within 3 days in Paris

Significant projects and collaborations

The research on humanoid robots is conducted in close collaboration with the Japanese institute AIST through the LIA JRL that became UMI in December 2008. It benefits from the HRP-2 humanoid robot platform acquired 2006.

The research conducted in Gepetto is based on a synergy with labs in neuroscience. The most influential one remains the LPPA from College de

France in Paris. An active collaboration is also conducted with the CERCO in Toulouse.

Kineo CAM, the spin-off of LAAS remains a privileged partner (PhD of J. Himmelstein in 2008) in the application of motion planning to product lifecycle management (PLM) and automated disassembly of mechanical parts by virtual mannequins [ACL129, ACL189].

Within LAAS, Gepetto is collaborating with RIS on human modeling for human-robot interaction (Locanthrope project), RAP on robot control and signal processing, and MRS (common PhD W. Suleiman and Binaur project).

Moreover the list of co-authors in Gepetto publications shows a large number of collaborations[1].

Research projects

- **Zeuxis** (2006-2009) has been the core project of the Gepetto group to structure its research. Supported by the *EADS Foundation* for 400K€, the project aimed at starting a long term research action focused on the computational modeling of the human being to develop advanced capabilities of interaction with the increasing number of computer controlled artifacts.
- **Locanthrope** (2008-2010) is supported by ANR. It gathers four labs: LAAS-CNRS (Coordinator, 200K€), LPPA (CNRS, Collège de France), M2S (Rennes 2 Univ.), Bunraku (INRIA, Rennes). The project argues that part of the internal cognitive state of a walking person may be observed from only few parameters characterizing the shape the locomotor trajectories. It aims at providing computational models of human locomotion as a way to simulate and plan human-like actions and interactions in both Robotics and Computer Animation.
- **PerfRV2** (2006-2009) is a project aiming at introducing the virtual human with the Product Lifecycle Management (PLM) domain. The project was conducted by CEA and INRIA and supported by ANR. It gathered 18 partners from academia and industry. LAAS (70K€) had in charge to develop motion planning algorithms for digital mannequins.
- **AMSI** (2006-2009) is a project tending to explore human-computer interaction (via haptics) to improve the disassembly technology in PLM. The project was supported by ANR and conducted by the company Haption. It involved the company Kineo, the CEA-LIST and LAAS. LAAS (80K€) was in charge to design new algorithms for automated disassembly.
- **ROMEO** (2009-2011) is a project of almost 10M€ tending to design a human-sized humanoid robot. The project is coordinated by the company Aldebarran and supported by the FUI. It gathers 14 partners from academia and industry. LAAS (250K€) has in charge the workpackage dedicated to motion planning and control.
- **RBLINK** (2009-2011) is a ANR "young researcher" project coordinated by the UMI JRL with LAAS and INRIA as partners. It is dedicated to reflex studies in humanoid robotics.
- **Toyota** (2009-2010) has contracted with CNRS for the purpose of technology transfer and customization of the software platform HPP.

Gepetto has initiated several other smaller projects in the framework of CNRS programs. Egocentre (2006-2007, ROBEA Program) and Roma (2008-2009, PIR NeuroInformatique) have been both dedicated to neurorobotics. A program JST-CNRS (2007-2009) is dedicated to visit exchange between Gepetto and AIST researchers.

Finally Gepetto has participated to Binaur, a project conducted by the company Navocap and dedicated to design localization systems for people with vision disability. For LAAS the project has been mainly conducted by the group MRS, the role of Gepetto being to study human locomotion models in that framework.

[1]In addition to the collaborations above:

- France: INRIA Rennes, INRIA Grenoble, University of Lyon, ISIR (Paris), ANIM (Paris), LSS (Sophia), IRIT (Toulouse), ENIT (Tarbes), GRAVIR (Clermont-Ferrand)
- Italy: University Roma 1
- Germany: Heidelberg University, TU Munich
- Belgium: KU Leuven
- Spain: University Carlos 3 (Madrid), University of Saragoza
- Switzerland: EPFL (Lausanne)
- China: Beijing University of Technology
- Australia: University of Camberra
- Russia: Keldysh Institute (Moscow)
- Mexico: CIMAT (Guanajuato)
- USA: Columbia University (New York)

Robotics, Action and Perception – RAP –

Permanent Staff:
Members: V. Cadenat (MC), M. Courdesses (P), P. Danes (MC), M. Devy (DR), A. Herbulot (MC), F. Lerasle (MC HdR), M. Renaud (P), T. Sentenac (CA)

Non Permanent Staff:
Postdoc : M. Fontmarty
PhD students : D.L. Almanza-Ojeda, J. Bonnal, D. Botero Galeano, B. Burger, J.M. Codol, B. Coudrin, B. Ducarouge, A. Durand Petiteville, S. Durola, T. Germa, A. Gonzalez, J. Harvent, M.A. Ibarra Manzano, D.A. Marquez Gamez, Y. Raoui, N. Sallem
Long term visitor: I. Zuriarrain

Objectives and positioning

The Robotics, Action and Perception research group (RAP) has been created September 1st 2006, from the new organization of the Robotics and Artificial Intelligence department (RIA). RAP mainly studies the functional capabilities of autonomous robots which must execute tasks in dynamic and evolutive environments. RAP research is focused on Perception and Action, i.e (1) how pertinent information could be extracted from sensory data acquired either from vehicles (robot, car…) or from sensors merged in the environment, and (2) how a vehicle could be controlled from these sensory data.
Since 2006, RAP has been reinforced by the recruitment of A.Herbulot (Sept. 2008) and by the HDR defense of F.Lerasle (Jan. 2008). RAP is highly linked with the other groups of the RIA department, and has been involved in several transverse activities, so that it has active internal collaborations with other LAAS research groups (MRS in MOCOSY, N2IS in MINAS and recently, OLC in SINC), through participations to joint projects or co-supervisions of PhD students.
Let us emphasize on some important evolutions:
- Vision (multi-spectral: color, infrared…) is the privileged sensor, either to detect, track or interpret events from image sequences, or to control robot motions from visual servoing.
- Applications concern mainly services to humans, so they require Human-Robot interactions or execution of navigation or manipulation tasks in human environments.
- RAP obtained first results in the integration of complex functions on dedicated architectures, either on smart cameras or on an audio sensor.
- From 2008, RAP has been actively involved in many collaborative projects, funded by ANR (4), FUI (1) or FP6 (1), requiring the hiring of many PhD students (11 defended thesis since 2005, 16 doctoral students in RAP in June 2009).
- RAP had very active collaborations with local SMEs, especially with the start-up NOOMEO created in 2007 by former PhD students of the RAP group, with the support of the RAP permanent staff.

Since its creation in 2006, RAP activities are organized in four interleaved themas, involving many cooperations between its members. Perception issues are studied in two themas, devoted to the *Visio-auditive perception and the interpretation of human activities*, and to the *Perception of the environment for navigation and manipulation tasks*. The developped perceptual functions are exploited by the two other themas, devoted to the *Modeling and Control of Complex Robotic systems* (e.g. visual servoing) and to the design and the development of *Communicating Integrated sensors* (e.g. smart cameras for vision, audio sensor).

Highlights and Major Achievements

Perception on the Environment for Navigation and Manipulation tasks.

"Objectives" — *A* robotic system must perceive the environment where a task (navigation, manipulation) has to be executed. For this purpose, it must at first build several representations of the environment and make use of these models during a task execution, in order to locate itself, to detect unforeseen events or to recognize and locate objects. RAP has worked mainly on three topics :
1) the mapping of indoor environments,
2) the perception for object grasping
3) and more recently obstacle detection.

"Methods"
Mapping of environments (PhDs : J.Sola, 2007; A.Zureiki, 2008): RAP has contributed on *Simultaneous Localization And Mapping* (SLAM), especially on EKF- SLAM. A mobile robot builds incrementally a stochastic map, from the fusion of features extracted from successive views using Extended Kalman Filtering. A Bearing-Only SLAM method has been proposed for the mapping of a static environment. 2D interest points are detected and tracked in successive images acquired from the embedded camera : a 2D pixel gives only an optical cone on which the corresponding 3D point is located. The main contribution concerns the undelayed initialization of the 3D point associated to a new

detected 2D pixel. At first in 2005, a Federated Information Sharing (FIS) method has been proposed to initialize without delay a 3D point by a set of Gaussian vectors in a stochastic map as soon as it is perceived in one image, and to select progressively only one estimate using next observations of the same point [ACL507, ACTI201]. Same results are obtained now using the Inverse Depth representation proposed by other authors in 2006. Then our approach has been extended to cope with different configurations :

- stereovision (Bi-Cam SLAM) [ACTI719],
- dynamic environment (SLAMMOT),
- observations acquired from several cameras mounted on different robots (SLAM-multi).

Recently the same initialization strategy has been applied for the reconstruction of 3D segments [accepted IROS2009].

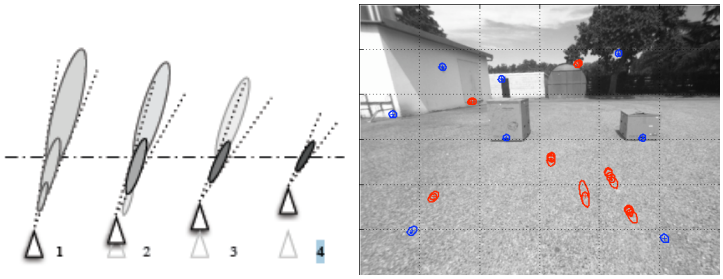


Figure 3 : The incremental reconstruction of a 3D point considering a conic optical ray. On the left, hypothesis selection using 4 views acquired by the mobile camera. On the right, an image with expectation ellipses for points (blue) and for rays (red).

Ongoing work concerns the learning of a robot trajectory using the same stochastic map framework.

Another work has aimed to build a textured and surfacic 3D map from 2D and 3D data acquired from a camera and a 3D laser range finder embedded on a mobile robot. Interest points or 2D segments are extracted from images, while 3D planar patches are segmented from range data. The SLAM framework [ACTI1242] has been proposed to fuse successive perceptions of these planes, and of points and segments supported by these planes ; texture is mapped on planes.

Perception for object grasping (PhDs : A. Restrepo, 2005; M.Cottret, 2007; F.Trujillo, 2008) : RAP has worked mainly on object detection [ACTI364], 3D mapping [ACL82] and recognition using an appearance representation [ACTI1425, ACTI688]. The detection of unknown objects that could be used as landmarks, was done thanks to a classical saliency map. The 3D mapping of unknown objects and the appearance-based recognition of known ones are based on interest points extracted from classical detectors (Harris, SIFT, Kadir…) or from a new Harris Laplace detector in color images, using a camera mounted on a manipulator, moved around an object. 3D reconstruction is obtained from nonlinear Optimization (Sparse Bundle Adjustment). An active recognition strategy has been proposed, using entropy maximization in order to select optimal camera positions to validate concurrent hypothesis about objects detection from images.

Obstacle detection (PhDs : G.Aviña [ACTI104], V.Lemonde [ACTI326] in 2005) : the problem consists in detecting mobile obstacles from data acquired from a robot. Stereovision-based or monocular-based methods were initially proposed ; ongoing work addresses obstacle detection from a belt of cameras (how to build a robot-centered occupancy grid from N cameras mounted around a robot ?) or from a single moving camera (how to segment several moving obstacles from the background, using a set of detected and tracked interest points ?).

A new project begins about obstacle detection from multi-spectral images acquired from an airplane moving on taxiways.

***Major Results*:** seven doctoral thesis were defended: J.Sola obtained the 2nd price of the best thesis from the GDR Robotics in 2008. Nine ones are still ongoing (D.Marquez, JM.Codol on topic #1; B.Coudrin, B.Ducarouge J.Harvent, Y.Raoui and N.Sallem on topic #2; A.Gonzalez and D.Almanza on topic #3).

Visio-Auditive Perception for the recognition of Human activities.

"Objectives" — Our research has concerned the detection and recognition of people as well as the interpretation of human motions, from visual and auditory sensors.

Our work in visual perception of humans has dealt with the tracking and interpretation of human movements. We have prototyped and evaluated functions robust to the environmental conditions and computationally cheap.

Within the newly launched research in robot audition, an auditory sensor has been built to the generation of "acoustic maps" of the environment and the extraction of sources, which fits the original constraints raised by robotics.

"Methods"

Visual perception of humans

For human motions tracking and their interpretation, probabilistic graphical models as well as particle filtering, because of its ability to easily and rigorously integrate diverse sensory percepts, are here considered. Several trackers were prototyped and evaluated, based on the selection of some visual cues, the probabilistic combination of person

detection/identification modules within advanced filtering strategies. This procedure has been applied to appearance based person 2D tracking [ACL522], as well as to the 3D tracking of either the whole body or body parts from embedded or fixed cameras [ACTI1380]. Besides, further investigations have coped with the multimodal fusion of vision and speech [ACTI1274] for the interpretation of speech commands parameterized by gestures *e.g.* deictic gestures.

Implementations on mobile platforms dedicated to interaction have enabled the validation of most of our visual functions on robotics scenarios (Figure 1) and have underlined their complementariness.

Figure 1: Interpretation of multimodal commands by the robot (left: hands and head tracking; center: synthetic top view; right: experiment)

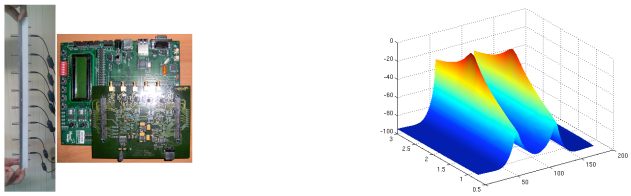


Figure 2: (a) Acoustic sensor. (b) MUSIC pseudo-spectrum, as a function of the source (range, azimuth)

Robot audition: sound source localization

A fully programmable integrated auditory sensor has been developed based on a linear array of 8 microphones, a dedicated acquisition chain and FPGA-based processing. The first aim was to compute acoustic maps of the environment at a rate of 15Hz, and to spatially filter sources out of the ambient noise [accepted IROS2009]. Constraints raised by Robotics are: embeddability (size, energy), real time, wideband sources (e.g. at least the bandwidth [300Hz;3000Hz] for voice), farfield or nearfield assumption, as well as ambient noise and reverberation. Following a localization strategy in azimuth and distance based on an original broadband farfield-or-nearfield beamforming algorithm [ACTI593], a second approach was proposed, combining this algorithm with a broadband extension of the high-resolution MUSIC (MUltiple SIgnal Classification) method [ACTI988]. A typical pseudospectrum, showing sharp peaks at the sources (range,azimuth) locations, is presented on Figure 2.

"Major Achievements" — They have concerned:
1) Detection, Tracking and Identification of humans;
2) Gesture and Speech based interaction;
3) Visual based markerless human motion capture;
4) Sound source localization and extraction (spatial filtering) – Higher-level auditory functions;

Three doctoral theses were defended (L.Brèthes, topic #1, 2005; S. Argentieri, topic #4, 2006; M.Fontmarty, topic #3, 2008), and three are still on-going (B.Burger with IRIT on topic #2, to be defended fall 2009; I.Zuriarrain with Univ.Mondragon and T.Germa on topic #1, to be defended spring 2010; J.Bonnal, topic #4, to be defended fall 2010).

Modeling and Control of Complex Robotic systems

"Objectives" — Here RAP researchers have studied the analysis and control of mobile robots using mainly visual servoing, possibly based on detection and tracking functions developed on the two other themes. Two approaches have been developed, using either

1) the "*task function*" paradigm for navigation in cluttered scenes (moreover in human environments)

2) or Lyapunov theory and Linear Matrix Inequalities (LMIs) for the analysis / synthesis of visual servos taking into account several constraints.

"Methods"

Vision-based navigation in cluttered scenes

This first approach addresses problems of both multisensor-based navigation and visual servoing of mobile robots. A first objective has been to perform navigation tasks in unknown environments on the basis of visual and range sensors. The considered environments are supposed static and may be cluttered with occluding and non-occluding obstacles. The first obtained results have shown that avoiding both occlusions and collisions over-constrains the robot motion and that it is not the most suitable strategy (figure 1) [ACTI669, ACTI1337, ACTI234]. We have then developed new techniques able to let the occlusions occur if it is required by the mission success (figure 2) [ACTI1275,ACTI876]. We have proposed a set of methods allowing to reconstruct the visual features when they are unavailable. We have compared the obtained solutions from different points of view (accuracy, swiftness, etc.) [OS67, ACL461,ACTI762]. Both experimental and simulation results have shown the

validity of the proposed approaches [ACTI1275, ACTI669].

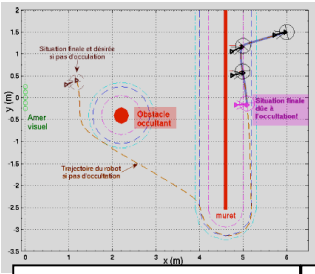


Figure 1: 1st kind of method: The task fails when the occlusion occurs

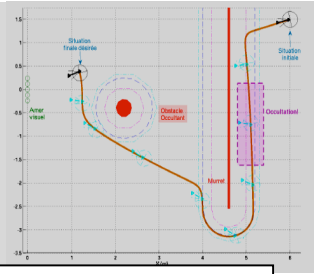


Figure 2: 2nd kind of method: The task is successfully performed despite occlusions

More recently, we have addressed the problem of executing vision-based navigation tasks with respect to humans in populated environments. This work has been initiated through the Commrob project whose global objective was to design a trolley able to assist a user in a shopping center. The system was equipped with a camera mounted on pan-tilt unit and the user was given a RFID tag to enhance the detection process. The considered task has consisted in making the trolley autonomously follow a user detected by an embedded human tracker or thanks to the RFID tag when he is not visible. We have developed a complete multi-sensor-based control strategy relying on the visual data provided by the tracker when they are available and on the RFID data when the user cannot be detected. This strategy has been experimented on Rackham robot and validated through numerous different experiments [accepted IROS09, CVIU09]. Following these results, we have improved the vision-based controller robustness by mixing sliding-mode techniques and the task function formalism classically applied to design visual servoing controllers. As previously, this control law has been experimented on Rackham and the obtained results have proven the efficiency of the chosen technique with respect to more conventional approaches [accepted ECMR09]. We have also studied the vision-based control law sensibility with respect to different errors on camera calibration parameters, depth and visual data noise [ACL296].

Multicriteria visual servoing

A second activity concerns the design of generic methods to the "multicriteria" analysis and synthesis of visual servos, i.e. taking account of all the constraints of the problem: convergence, visibility, actuators saturations, exclusion of 3D areas, singularities avoidance, etc. We have proposed a sound and versatile approach, which consists in recasting the multicriteria analysis (resp. synthesis) of many visual based positioning schemes as the stability analysis (resp. the stabilization) of a nonlinear rational system subject to rational constraints. Advanced control strategies have then been sought, expressing the stability/stabilization conditions as the minimization of a convex criterion subject to Linear Matrix Inequalities (LMIs). Such optimization problems are indeed convex and can be solved with available dedicated software at a moderate complexity.

The first results were developed within the framework of quadratic stability. As the symmetry and convexity properties of the consequent ellipsoidal invariant sets is penalizing in this robotics context, nontrivial extensions were proposed in [ACL125].

In collaboration with Daniel F. Coutinho, associate professor in control at PUCRS, Porto Alegre, Brazil, alternative solutions were then developed to convert the Lyapunov based analysis conditions into LMI problems. Interestingly, these enabled the use of more involved Lyapunov functions, e.g. biquadratic [ACTI468] or piecewise biquadratic [ACTI663], leading to much less conservative conclusions [ACTI1472].

Prior to the research period related herein, it had been shown that our statement of the visual servoing problem induces a striking duality—in the sense of the duality between control and estimation—between visual servoing and visual based localization. A new approach to set-membership filtering of rational systems has been developed [ACTI1414], to be applied to the visual based localization problem.

"Major achievements" — One doctoral thesis was defended (D.Folio on the topic #1; 2007) and two ones are ongoing (A.Durand Petiteville on the topic #1, S.Durola on the topic #2) .

A paper on topic #1 obtained the best paper price in the ROBIO2006 conference. Work on topic #2 has given rise to lectures at the French research groups in control (GdR MACS) and in robotics (GdR Robotique), and to invited talks in some foreign universities (Coimbra, Bogotá).

Network of Integrated Sensors

"Objectives" — In this more prospective topic, RAP has initiated work aiming at the design, development and evaluation of integrated sensors. In a long-term objective, a system is seen as a network of integrated and decentralized units, communicating to each other, high level and abstract information in order to achieve a common goal : this concept can be applied for a robot or for a monitoring system made of a network of smart cameras. During the last period, RAP has cooperated with other LAAS research group in order to study the hardware and software architecture of sensory systems able both to execute complex algorithms (dense stereovision, detection and tracking of humans, obstacle detection on vehicles), and to satisfy hard constraints like real

time performance, compacity and autonomy (low power, wifi communication).

"Methods" — The design and the implementation of an integrated stereovision sensor, were studied in the context of the internal PICAS$O LAAS project [ACTI1512, ACTI1953]. The first version developed on an Altera evaluation system (Quartus, Stratix kit) provided 640x480 disparity images at 100Hz ; it is currently improved and adapted to be executed on a compact processing unit (6x6cm cards with Cyclone2 FPGA, connected to cameras through CameraLink interfaces, see fig.4), developed with the SME Delta Technologies Sud Ouest (DTSO).

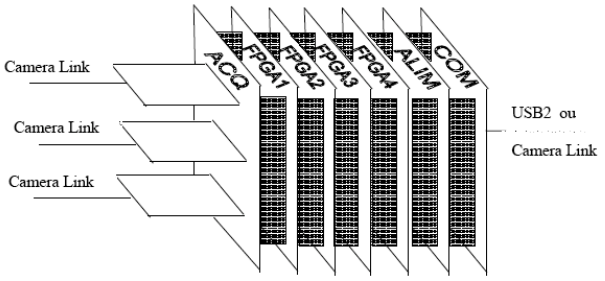


Figure 4 : Architecture dedicated to the dense stereovision algorithm

Besides, research work has been initiated about the development of new algorithms on human detection and tracking from a network of integrated monitoring cameras developed also by DTSO, so based on the same FPGA cards. This research work began in the context of a project with University of Mondragon in Spain, and will continue with the project CameraNet funded by the Midi-Pyrénées region. The aim consists in the adaptation of functions developed in order to detect and track humans using particle filtering, then in the integration of these functions on the camera, and finally on the achievement of monitoring tasks by a wifi network of such cameras, exchanging information on the environment state.

Finally concerning obstacle detection, ongoing work tackles the design and the implementation of an obstacle detection system to be integrated on a robot or a vehicle. It is made of N micro-cameras (N=8 for the first version) interfaced with a FPGA-based processing unit, now a StratixIII development kit. Three steps are required : at first the detection of potential obstacles from a classification of every pixel on every image as Ground or Obstacle, based on color-texture characteristics ; then a validation based on spatio-temporal analysis, using an estimation of the robot motion between successive acquisitions ; and finally, the fusion of all results in a probabilistic robot-centered occupancy grid, sliding with the robot during motions. This occupancy grid will be updated and sent to the robot control unit, at 30Hz [ACTI1501].

RAP (in cooperation with the N2IS group) will study how to integrate on a dedicated architecture, algorithms developed for obstacle detection from multi-spectral images acquired on an airplane moving on taxiways.

"Major achievements" — One doctoral thesis was defended in the N2IS research group on the PICAS$O project in 2006, and two ones are ongoing (D.Botero and M.Ibarra on obstacle detection, co-supervised with JL.Boizard from the N2IS group): another one will begin in 2009 on smart cameras for monitoring applications.

Significant projects and collaborations

RAP has participated to many projects during the last period, funded either by Europe, ANR, FUI, the Midi-Pyrénées region or directly by companies. Let us note the end of two collaborations on Intelligent Transportation Systems in 2005.

The most significant project was the EU project FP6-IP-COGNIRON (The Cognitive Robot Companion, 2004-2008): RAP was involved on visio-auditive perception of humans and on the construction of spatial or object representations.

Many works are still developed in the context of on-going projects: let us mention an AIRBUS funded project on Non Destructive Testing (in cooperation with Ecole des Mines Albi-Carmaux) , ANR funded projects AMORCES (human-robot interaction), ASSIST (vision for manipulation with two arms), RINAVEC (SLAM for convoy navigation) and R3T (thermal and 3D metrology). Since 2007, RAP has participated to the FP6-STREP COMMROB (Advanced Behavior and High-Level Multimodal Communication with and among Robots) devoted to the development of a service robot assisting clients in a commercial center: RAP manages the technical integration, is responsible for human-robot interaction and participates to works on RFID-based navigation and on obstacle detection.

RAP helps several local SMEs, using CIFRE contracts and/or regional projects: DTSO (on smart cameras), ORME (analysis of video sequences), NAVONTIME (with the MRS group, on hybrid GPS-Vision navigation) and NOOMEO (with EMAC, on 3D modeling).

Finally RAP has been involved in several international cooperations with Brazil (robust control), Japan (audio perception), demining and integration (Colombia, from two successive ECOS actions), vision for navigation (several partners in Mexico), vision on humans (Coimbra in Portugal, Mondragon in Spain).

Robotics and InteractionS – RIS –

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Objectives and positioning

The "Robotics and InteractionS" (RIS) group conducts research on the autonomy of machines that integrate perception, reasoning, communication, learning, action and reaction capabilities. Our efforts are essentially oriented toward decisional, algorithmic and architectural issues for robot and multi-robot systems. Our approach proceeds from the need to consider the robot as a whole regardless of frontiers between disciplines. Perception and action abilities are studied in synergy with the other groups in the "Robotics and Artificial Intelligence" Area. In the reporting period, RIS worked along two complementary perspectives (Figure 1):

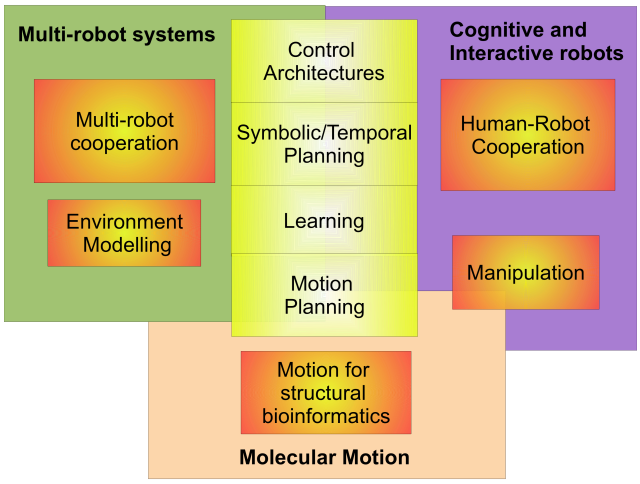


Figure 1: RIS domains and contextual perspectives

- **A fundamental perspective** where we develop models and algorithms for decisional problems. This concerns symbolic task planning and learning as well as geometric motion and manipulation planning for highly complex systems.
- **A contextual perspective** where we investigate three concrete subjects as challenging contexts for the methods we study and also as sources of new scientific questions raised by confronting the available methods and tools to realistic and ambitious application domains.

The three subjects are:

1. **Cooperative multi-robot systems** and more particularly the aerial-ground context involving several heterogeneous networked robots to achieve environment perception-based missions.
2. **The cognitive and interactive robot** and more particularly the autonomous mobile robot assistant that has to achieve manipulation tasks in cooperation with humans.
3. **Molecular motion problems** using robotic algorithms to explore new computational routes for structural bioinformatics.
4. In terms of positioning, RIS contributes and cooperates at the forefront of research in its domains. We summarize, in the sequel, the corresponding investigations and results, and the collaborative projects in which they are conducted.

Highlights and Major Achievements

Fundamental methods and algorithms

"Robust and Dependable Architectures for Autonomous Robots" — Recent developments, especially in service robots, put the robot in close vicinity and in direct physical interaction with humans. However, little has been achieved, until now, to address the issue of safety and dependability of robot software in such demanding context. It becomes critical to provide a formal approach which guarantees that safety rules and properties related to robot software components interactions are enforced.
In the last years, we have teamed with VERIMAG and came up with an approach that combines their BIP (Behavior, Interaction, Priorities) component-based design approach with our modular architecture development approach.
The LAAS architecture proposes a software organization and provides a set of associated tools [ACL327, ACTI99, ACTI100, ACTI405]. One of the tools, GenoM, allows to build robot modules by instantiating a unique generic canvas. What differentiates GenoM from most robotics middleware is that not only it provides a clear API for the services offered by modules, but also a clear and clean organization of their implementation. We applied the BIP methodology to GenoM by building a BIP model of the generic LAAS architecture

components in order to automatically synthesize "BIP modules" (Figure 2).

A result [ACL579, ACTI1214] of this work is the synthesis of a BIP model of the complete functional layer of the DALA rover, which allows us to:

- Generate a rover controller which is correct by construction and can be run by the BIP engine.
- Check if the model satisfies particular properties and constraints, by using a V&V (Verification and Validation) tool such as D-Finder developed by VERIMAG.

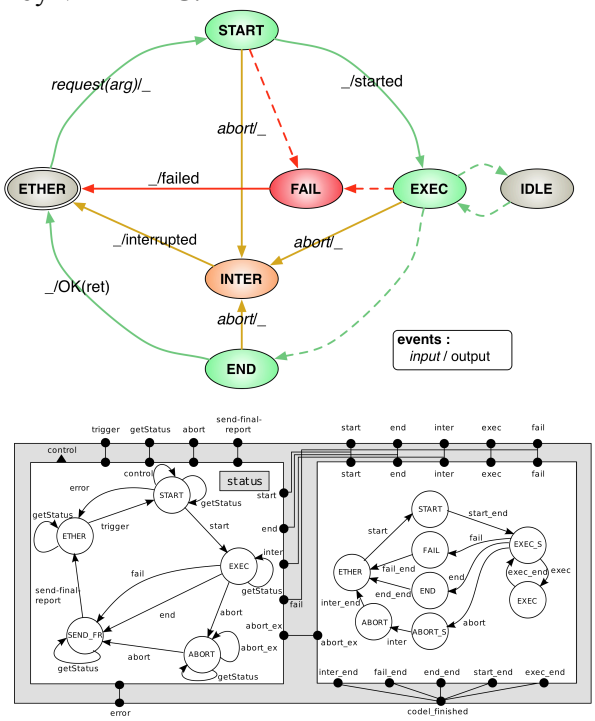


Figure 2: The Activity Automaton of a GenoM module (top) and the equivalent BIP model (bottom)

"Temporal Planning and Execution Control" — Robot planning for acting in the real world requires explicit time. Moreover, the plans/policies produced should be robust and leave some flexibility to the plan execution controller. Such flexibility can be obtained in various ways. One can allow events to occur in a temporal interval, or provide local repair mechanisms, or the plan can propose multiple execution paths. However, there are other paradigms "outside" the Automated Planning field which may prove to be successful with respect to this objective.

We have compared two "planning" approaches. The first one is based on chronicles and constraints satisfaction techniques and relies on a causal link partial order temporal planner, in our case IxTeT [ACL327]. The second approach is based on timed game automata and reachability analysis, and uses the UPPAAL TIGA (TImed Game Automata) system. This work lead to both a qualitative (i.e. the kind of problems modeled and the properties of plans obtained) and quantitative (experiments on a real example) results. This comparison was done thanks to a general scheme, that we proposed, which translates a subset of IxTeT planning problems into TIGA game-reachability problems. We have shown that a "classical" rover exploration problem can be modeled in UPPAAL TIGA and produce plans with a temporally robust execution policy. The comparison shows that each has its advantages and drawbacks. However, having the possibility to use formal methods from timed automata to prove properties of a given plan model is very encouraging with respect to the acceptability of automated planning in critical timed systems [ACTI906, PhD M. Gallien].

"Learning" — Autonomous robots are able to achieve more and more complex tasks, relying on sensory-motor functions. To better understand their behavior and improve their performance, it becomes necessary to characterize and to model at the global level how robots behave in a given environment [ACL143, TH76].

We have developed a general framework for learning, from observation data, the behavior model of a robot when it is performing a given task. The behavior is modeled as a Dynamic Bayesian network (DBN) that can be learned (using a modified version of Expected Maximization with Particle Filtering) and it can be used to improve on line the robot behaviors [ACTI502].

"Algorithmic motion planning" — A strong axis of the research conducted in RIS concerns the algorithmic foundations of motion planning for complex articulated systems. Our work, first initiated by the *MOVIE* EU project (2003-2006) and then continued in the framework of the *PHRIENDS* EU project (2006-2009), has contributed to the development of the sampling-based methods that have now emerged as an efficient framework for facing the high complexity of motion planning. Our contributions concern the two main classes of methods: the *Probabilistic Roadmaps* sampling algorithms (PRM) and the *Random Trees* diffusion variants (RRT) developed for solving multi-query and single-query problems, respectively. The obtained results extend the state of the art to better face the complexity of the search spaces (constrained and highly dimensional) and of the mechanisms (closed-chain systems), as well as to incorporate additional motion constraints (dynamic obstacles, path quality and uncertainty).

A first result concerns the extension of the PRM framework for reactive planning in dynamic scenes with both static and mobile obstacles (TH49). The proposed hybrid planner builds on the *Path Deformation Roadmap* (PDR) technique [ACL515, ACTI489] to pre-process high quality roadmaps, capturing the multi-connectedness of the configuration space with small graphs which are yet

representative of the varieties of feasible paths, and that allow efficient dynamic updates. The approach integrates also an improved *Dynamic Domain sampling* technique (DD-RRT) to efficiently repair roadmaps edges invalidated by the moving obstacles [ACTI198, ACTI116] (joint work with S. Lavalle's group from Illinois University). Besides, an alternative roadmap construction technique has been proposed in collaboration with M. Overmars (Utrecht University) for the specific case of *a priori* known placements of moving obstacles [ACTI987].

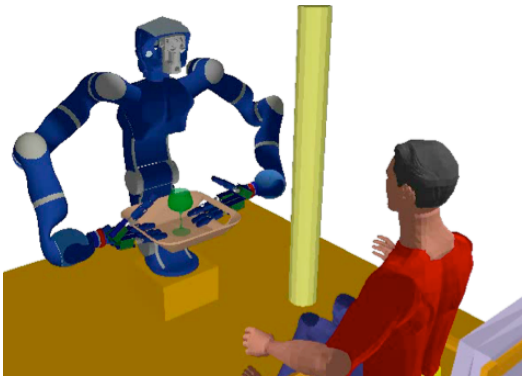


Figure 3: Motion planning for a complex humanoid torso

While state of the art methods address constrained disassembly problems for rigid objects, our contribution with the *Manhattan-Like* algorithm (ML-RRT) is to handle more complex problems with articulated objects [ACL431, ACTI742]. The efficiency of the method allows us to tackle the complexity of highly challenging models with hundreds of degrees of freedom in structural bioinformatics applications [ACTI706] (see 2.3). Another recent contribution to diffusion methods concerns path optimality, with a new technique (T-RRT) combining *Transition tests* used in stochastic optimization, that first bridges the gap between cost space and configuration space planning [ACTI-1276].

Regarding uncertainty, our contribution with the *Stochastic Motion Roadmap* (SMR) developed in collaboration with K. Goldberg (UC Berkeley) is to extend the PRM framework to robot motion uncertainty [ACTI819, INV37]. SMR combines a sampling-based roadmap representation of the configuration space with the well-established theory of MDPs to maximize the probability of avoiding collisions and successfully reaching the goal. This sampling technique is shown to be far more efficient than previous Markov motion planning approaches based on grid-based searches.

Finally, our previous results on closed-chain planning have been strengthened to solve complex coordinated manipulation tasks with multi-arm robots requiring reconfigurations through singularities [ACTI1230]. For specific loop linkages, a decomposition-based method satisfying a stronger completeness property has been also investigated in collaboration with F. Thomas in Barcelona [ACTI987].

"Asymov, a hybrid task planner" — We also addressed the challenging issue of bridging the gap between symbolic and geometric reasoning. We have extended our work on the manipulation planning problem and come up with a general framework to solve intricate motion, manipulation and task planning problems. We introduced a new extension to classical action planning formalisms with a rigorously defined interaction between action and motion planning. On this formal basis, we have built a planner that is able to solve intricate geometric and symbolic constraints that are not solved by any other planner [ACL561, TH18]. It is worth noting that the concept of manipulation planning that we have developed has inspired a number of new algorithms and geometric reasoning approaches.

Three research subjects and contexts

"Multi-robots systems" — Our long-term goal is to develop a comprehensive robot architecture for multi robot systems that allows a wide variety of cooperation schemes [DO08]. In multi robot systems, communication constraints and the fact that various robots endowed with different autonomy levels will eventually have to cooperate call for distributed decision-making systems.

In this context, we have proposed various contributions, which renew and extend our activities in this area [ACL47]. The particular case of UAV formation flight has been studied. Here, a set of UAVs must traverse an area while avoiding various threats. Each UAV is endowed with a single threat protection system, and the formation must be continuously updated so that the UAVs protect themselves. We have proposed an intermediate decision layer that connects the mission planning layer and the flight control layer, which is dedicated to the management of the geometric configurations of formations. This layer assigns relative positions to the UAVs and handles the reconfiguration trajectories that allow to switch between the defined configuration, respecting security constraints on inter-UAV distances. The approach has been evaluated in realistic simulations and actual experiments with three 1.0m wingspan fixed-wing UAVs [ACTI589, ACTI962].

From a more general point of view, we have been working on a "plan manager", a component that provides the services needed to build, update and execute plans in a multi-robot context. This component handles the insertion and removal of tasks, provides tools for safe concurrent execution and modification of plans, and handles distributed plan supervision without permanent inter-robot communication. It relies on the definition of a plan

model and a set of operations on plans abstracted from various contributions to multi-robot planning. An execution scheme for this plan model, based on a plan modification tool has been developed and can be used to integrate various plan-based negotiation protocols [ACL572].

Figure 4: DALA and NIRVANAs

"Environment modelling" — Most of our activities in environment modeling have been devoted to the development of simultaneous localization and mapping processes based on vision, be it monocular, stereoscopic and panoramic. This work, carried out in collaboration with the RAP group, has led to significant achievements [ACL346, ACL279]. Recently, the problem has been extended to the multi-robot case: an approach that relies on hierarchical SLAM has been proposed, in which each robot builds a set of independent submaps, and an overall graph that links the frames associated to each submaps maintains the spatial consistency of the maps over large scales. Inter-robot perceptions, GPS fixes or map matches among robots yield constraints on the graph that are propagated using a global optimization scheme.

The focus is now on SLAM approaches that rely on more complete geometric primitives than points detected in images [ACTI273].

Besides work on SLAM, we have developed an approach to assess the traversability for a rover from a sequence of aerial monocular images [ACTI598]: this work is intended to the development of effective air/ground multi-robot cooperation.

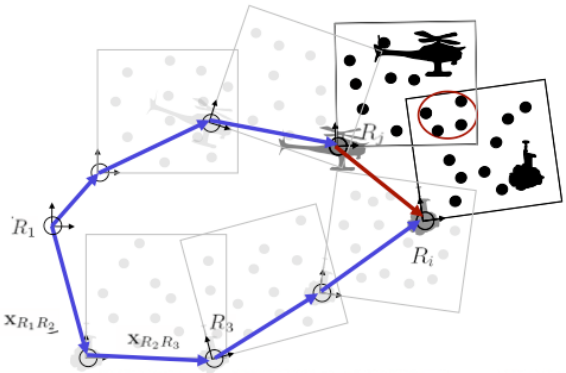


Figure 5: SLAM in multi-robot air/ground context

"Toward a robot companion" — This reporting period gave rise to the development of a new topic: the robot companion. The subject was initiated in the preceding period by a first national ROBEA project (HR+) [ACTI543] and then COGNIRON, a 4-year IP lead by LAAS in the framework of the FP6/FET "Beyond Robotics" initiative [INV42]. Researchers from RIS coordinated the overall project and investigated more particularly decisional and multi-modal interaction for a robot in presence and even in synergy with humans.

One key element, in the approach, was that the human is explicitly taken into account in the system [ACTI594, ACTI880]. We have developed a complete robot control architecture adapted to human robot interaction and investigated various issues such as a supervision system dedicated to collaborative task achievement as well as models and algorithms for human aware task and motion planning.

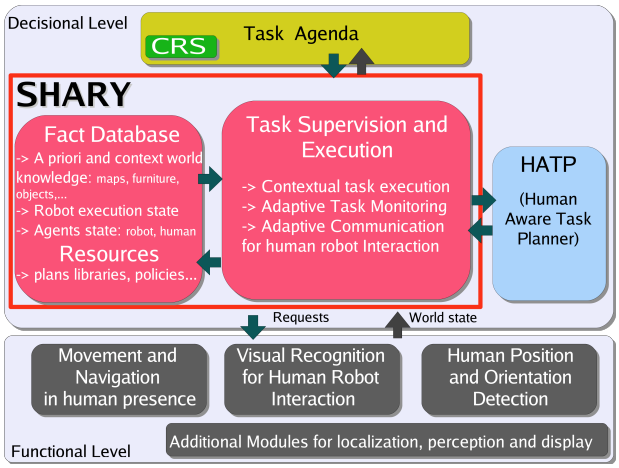


Figure 6: Architecture of the decisional level for HRI

Several aspects have been considered such as efficiency and safety in task performance but also acceptability and legibility of robot behavior. New original concepts have been identified and developed through an effective collaboration with several partners within the project.

The robot supervisor, called SHARY (Supervision for Human Robot Interaction), is based on the notion of joint human-robot goal achievement. It embeds a set of mechanisms that allow integrating multi-modal communication in order to support interactive task achievement [ACTI1229].

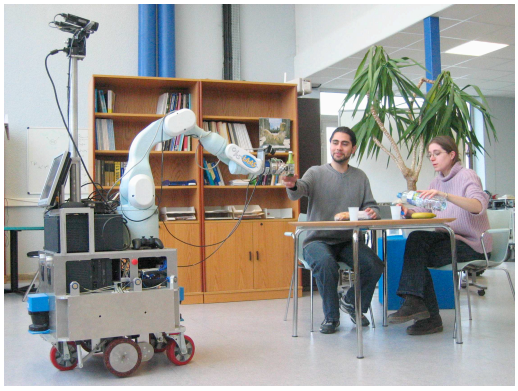


Figure 7: A scenario for Human-Robot Interaction

Another component, called HATP (Human-Aware Task Planner), based on HTN, that implements task planning for a robot assistant based on the notion of socially acceptable robot plans [ACTI1373]. Motion planning in presence and/or in cooperation with human has also received special attention. We have developed a Human Aware Navigation Planner as well as a Human Aware Manipulation Planner, which are based on these user studies, and which produce not only physically safe paths but also comfortable and legible paths [ACL356, ACTI960, ACTI1073].
These three aspects have been investigated through three PhD theses [TH114, TH184, TH186].

"Manipulation in interaction with Humans" — We also devoted substantial efforts to planning and control problems of manipulation tasks in human environment.
We have built a planner capable of synthesizing a complete manipulation task defined by an object to grasp and to hand over to a human [TH65, ACTI112, ACLN22, ACTI376]. This first version was then improved to manipulate complex non-convex objects using decomposition method and inertial heuristics.

As our grasp-planning algorithm is based on the sampling of an important number of grasps, a fast and relevant grasp quality measure is needed. We worked on general criteria to qualify the grasp and more particularly on force closure which defines the capability for a grasp to balance any external force. Using central axes approach, we reformulate the problem as a linear programming problem (LP) whose optimal solution defines a quantitative measure of the force closure grasp [ACL366, ACTI1129, ACTI761].

Figure 8: Several planned grasps considering object shape and placement, as well as robot geometric and kinematic model

An important problem, still little addressed, is the transition from planning to control. We have developed and integrated to Move3D a soft trajectory planner [ACTI1277]. It is based on a series of cubic that limit velocity, acceleration and jerk. The first advantage of this original solution is to directly define a trajectory that synchronizes the different elements in movements. The second advantage is the uniformity of the representation of movements from the planning level to the control level [TH122, ACTI591, ACTI504, ACTI303].

"Overall integration" — One salient result is the integration of all the developments in one complete robot system, the fully equipped Jido robot. This allowed us to build and deploy a first and coherent global approach of the robot companion paradigm. Jido has been successfully demonstrated at the final review of the COGNIRON project. It embeds a large number of software components integrated thanks to the generic LAAS architecture and tools.

Motion for structural bioinformatics

Computational tools are today of primary importance for biologists to model protein structure and function, and understand biomolecular interactions. In this context, our goal is to explore new computational routes for structural bioinformatics, using robotic algorithms. This interdisciplinary research, started in 2003, has been reinforced during the period, and structured according to the ITAV project ALMA (2006-2009) conducted by LAAS in collaboration with biologist partners. The algorithmic challenge comes from the complexity of molecular chains involving up to thousands degrees of freedom. Our results show the high potential of these new techniques for modeling macromolecular flexibility as well as studying ligand-receptor interactions.

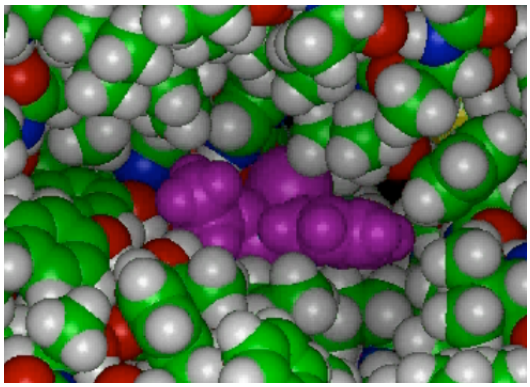


Figure 9: Planning for ligand-receptor interactions

The driving idea of the mechanistic approach [ACL62] is to separate the conformational search in two stages aiming at speeding up substantially the computation. The first stage consists in a geometric filtering using motion planning techniques applied on articulated hard sphere models, whereas the second stage accounts for the energy-based refinement of the solution paths. Our solution, combining the efficiency of a motion planning based conformational search [ACL431, ACTI706, ACTI1473] with fast geometric operators [ACTI145], is well adapted for exploring high-dimensional, constrained search spaces. This technique permits to globally explore molecular mobility and to efficiently compute large conformational changes. It has been validated in [ACL62] for two kinds of challenging problems involving large-amplitude motions: conformational changes due to long flexible loops and ligand pathways to deep active sites in proteins (Figure 9). In both cases, results show a speed-up of several orders of magnitude compared to molecular dynamics simulation.
The approach has been applied, in collaboration with biologists at LISBP, for studying the enantio-

selectivity of enzymes presenting a deep catalytic pocket. Promising results [ACL443] have been obtained with first models correlating the functional dynamic of the receptor to the difficulty of the access pathways. Our results indicate also that the approach can provide highly valuable information to biologists for site directed mutagenesis.

The conformational search technique was extended in [ACL618] to compute macromolecular deformations (e.g. domain motions such as open-closed transitions in proteins), considering fully flexible models (thousand of torsion angles). Such high complexity is handled by guiding the motion planning based conformational search using the directions of collective motions given by normal mode analysis (NMA). Indeed, the algorithm explores the space of the collective degrees of freedom, which has a much lower dimension than the original space. This dimensionality reduction technique allows to explore large-amplitude transition motions in an efficient way. It has been successfully applied to study transition motions between the open and closed structures of several protein models and the obtained results correlate well with the literature.

The above results lie at the front line of the current research in structural bioinformatics. Only few leading US groups in robotics, in particular at Stanford, investigate similar application of motion planning research for studying molecular motions.

Highlights and Major Achievements

The reporting period has been very intensive in terms of PhDs activity: 21 PhD theses[1] and one HDR have been defended. RIS developed strong cooperative links with a number of research labs in France and abroad. We co-authored 17 papers with researchers from 16 labs (5 in France and 11 abroad). The group has also hired 10 Postdocs and welcomed 8 visiting scientists[2].

Between March 2004 and November 2006, the robot Rackham has been deployed as a fully autonomous exhibition guide at the Cité de l'Espace (100 days in nine venues). It guided around 8000 visitors in a crowded environment. Rackham has also been demonstrated at Hertfordshire during RO-MAN 2006. Jido, the interactive mobile manipulator, has been demonstrated successfully at the FET-09 event (Prague, April 2009). Another notable achievement is the synthesis of a BIP GenoM robot controller that is correct by construction and which runs the DALA robot.

Significant projects and collaborations

Several collaborative research projects have been conducted. Regarding European projects, COGNIRON project, led by the group, has been fully achieved, and RIS has also been strongly involved in two FP6 Projects: PHRIENDS and URUS. RIS is also heavily involved in the ACTION (DGA/PEA) project as well as in several projects supported by ANR, ITAV, CNES, Région Midi-Pyrénées. The group has also collaborated with THALES, DASSAULT, IFREMER, ONERA and CNES.

The period has also been very successful in terms of projects construction. Several proposals have been submitted and accepted at national and European level. All of them feed directly the main group research topics and are fully in-line with its scientific roadmap.

List (non exhaustive) of projects corresponding to the reporting period

- COGNIRON - FP6/ /IP FET - (Jan 2004 - April 2008) coordinator - HRI - Cognitive architecture - Human aware motion planning
- PHRIENDS - FP6 (Oct. 2006 - Oct. 2009) - Motion planning / Human aware motion / safety
- URUS - FP6 (Nov. 2006 - Nov. 2009) - Control Architecture, Multi-robot cooperation, HRI
- ALMA - ITAV (Oct. 2006 - Oct. 2008) - Molecular motion
- AMAES - ANR (Nov. 2005 - Nov. 2008) - Control Architectures - Validation - Planning
- ACTION PEA-DGA (Jan. 2007 - Jan. 2014) -- Control Architectures - Multi-robot cooperation - Perception and Environment Modelling
- AGATA - CNES (Dec. 2005 - Dec. 2007) - Control Architecture - Planning
- CAVIAR - ANR (Jan. 2006 - Jan. 2009) - Perception and Environment Modelling - Navigation
- 2RT-3D - ANR (June 2007 - June 2009) - Perception and Environment Modelling - Navigation
- TAROT - ANR (Oct. 2006 - Oct. 2009) - Perception and Environment Modelling - Navigation
- ALCHIMIE: ANR - Perception UAVs

The list of new or recent projects can be found in the prospective section.

[1] A. Baba, S. Bosch, S. Cambon, A. Clodic, N. Do Huu, M. Gallien, J. Gancet, G. Hattenberger, I. Herrera Aguilar, G. Infantes, L. Jaillet, S. Joyeux, T. Lemaire, A. Lampe, E. Lopez Damian, V. Montreuil, T. Peynot, F. Py, E.A. Sisbot, L. Solaque, P. Theodorakopoulos

[2] R. Arkin, D. Asmar, M. Fox, J.L. Gordillo, A. Kelly, S. Sukarieh, S. Thiebaux, G. Verfaillie.

Research domain
Critical Information Systems – SINC –

Scientific Topics

The research issues addressed within the ***Critical Information Systems*** (SINC) area relate to the design and analysis of complex computerized systems that must satisfy stringent properties imposed by crucial applications. These properties are expressed by a set of requirements on temporal constraints, security, quality, resilience and co-operative operation.

The activities that justify the denomination of this research area are: the definition, exploitation and tooling of methods and techniques, both formal and experimental, for the design, verification, evaluation and development of critical software-intensive systems. The challenges concern the complexity and the strong interactions that ever more characterize the systems being considered and also relate to the emerging requirements for mobility, autonomy and evolvability. The main topics covered include:

- The engineering of complex systems through an interdisciplinary process, focusing on system design and evaluation processes.
- The formal specification, verification and test of software, with an emphasis on the integration of related tools within the industrial development process.
- The quality of service of distributed architectures, communication protocols and networks for co-operative and computation-intensive applications.
- The resilience and dependability of embedded computer systems with respect to various aspects: interactions between the components, mobility of either the users, the devices or the services, etc.
- The quantitative evaluation of the properties by stochastic modeling and metrology in real or simulated environments, under nominal or disturbed operation and by the analysis and characterization of the observed behaviors.
- The definition of policies and models and the development of new technologies, for accommodating both security and privacy concerns.

The Research Groups

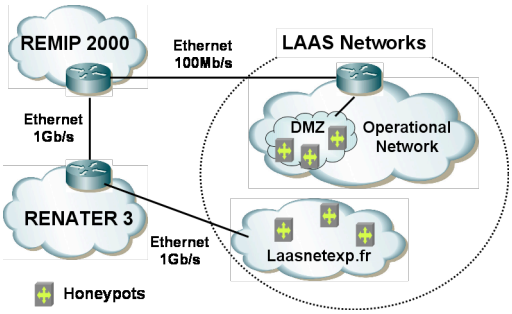
SINC is aimed at stirring up scientific exchanges among the four research groups ***Software and Tools for Communicating Systems*** (OLC), ***Dependable Computing and Fault Tolerance*** (TSF), ***System Engineering and Integration*** (ISI) and ***Distributed Computing and Asynchronism*** (CDA), that currently compose this research area[1] and whose research activities are respectively focusing on:

- The design of protocols and communication services for emerging network technologies and the new Internet generation, to support advanced distributed high speed multimedia and co-operative applications, as well as the study of formal description and verification techniques targeting critical systems.
- The design, test and evaluation of computing systems with strong dependability requirements (availability, reliability, safety and security) and thus accounting for a wide spectrum of faults: accidental faults (physical and software) and malicious faults.
- System engineering techniques, with an emphasis on the integration of models along three complementary directions: modeling of the heterogeneous systems, model-based requirement engineering and design, simulation and co-simulation of complex systems.
- The distributed and asynchronous computing paradigms: asynchronous algorithms suited to networking environments (especially, by implementing peer-to-peer distributed computations). The research also covers self-organizing interactive systems.

The Main Application Domains

The categories of systems addressed range from embedded systems (e.g., transportation and space), including also ubiquitous systems, to large-scale networks managing critical infrastructures, such as the distribution of electrical energy or air traffic control. Research results are exploited within many international and national co-operative projects: Noteworthy are the coordination of the FP6 Network of Excellence ***ReSIST*** (*Resilience for Survivability in IST*) and the many contributions to the Competitiveness Clusters: ***Aerospace Valley*** and ***System@tic***.

As an example of shared resources, the ***Laasnetexp*** network is a platform that jointly used by OLC and TSF groups for analyzing malevolent activity on the Internet, in particular in the frame of the French RNRT project ***OSCAR*** (*Overlay network Security: Characterization, Analysis and Recovery*). Honeypots have been deployed on the two LAAS networks: the "open" ***DMZ*** zone of the operational network, and the experimental network ***Laasnetexp***.



Deployment of honeypots

[1] Initially, SINC gathered the OLC and TSF groups. ISI joined in January 2007 and CDA was created in October 2007.

Tools and Software for Communication – OLC –

Permanent Staff:

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Non Permanent Staff:

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Scientific Topics

The research topics of the OLC group include the design, analysis, verification and experimental evaluation of critical communicating systems. Such systems are subject to strong temporal constraints and strong requirements in terms of quality of service and security.

The group participates in an important transfer activity in collaboration with other public laboratories and industrial companies including AIRBUS, AKKA, Alcatel-Lucent, Bull, Continental, C&S, EADS, France-Telecom R&D, Thales.

The group is involved as a participant or a coordinator in a number of research projects in different program frameworks. The contributions include:

- Self-adaptive protected heterogeneous networks, providing quality of service
- Related distributed cooperative and service-oriented applications
- Modelling and verification techniques for timed systems.

Highlights and Major Achievements

The OLC group is organized around three research axis: "**Formal description techniques**", "**Communication, Architectures and Protocols**", and "**Services and Components for Collaboration**".

Formal description techniques

The increasing complexity of critical systems requires to improve the methods and tools of systems engineering. Formal description techniques (FDT) - by their mathematical foundations associated with the existence of automatic verification techniques (model-checking) and the availability of tools to carry these verifications- help to handle this complexity. Our goals are to increase the expressiveness of these formal techniques in particular concerning temporal aspects, the effectiveness of the associated model-checking algorithms and the integration of these formal techniques with the processes of systems engineering.

The **contributions** over the last period include:

"Integration of formal techniques into the user's processes" — The approach we explore for improving that integration consists of coupling semantically the description methods used in the industry (AADL, SDL/UML, etc) with the formal notations used for verification [DO 2, ACTI356]. We proposed – in collaboration with IRIT and INRIA/VASY – a formal intermediate language, Fiacre [ACTI1043], that serves on one hand as the target language into which user-descriptions are translated (and given a formal semantics by that process) and on the other hand as a compact formal notation from which can be derived the low level descriptions used by verification tools like TINA and CADP (cf sec Tooling). Other experiments have been conducted, coupling Turtle – a real-time UML profile [ACL247] – and TINA, through the RT-LOTOS process algebra [ACTI237, ACTI265, ACTI565, ACL86].

"Formal techniques for the description and verification of real time systems" — Over the period considered, we investigated Time Petri Nets (TPN's) extended with:

- *External data:* we defined "Time Transition Systems", a format accepted as input by our tools that serves as target format for the verification of systems described in high level notations like Turtle, RT-Lotos or Fiacre.
- *Priorities* [ACTI563, ACTI989]: In addition to their convenience for modeling, we shown that priorities strictly increase the expressiveness of TPN's and makes possible to model real time systems in a compositional way. Concerning their analysis, TPN's with priorities can be handled with simple extensions of the available techniques for TPN's.
- *Stopwatches* [ACL88, ACL314]: Several extensions

of TPN's have been proposed for modeling suspension and resumption of actions in timed systems. Over the period we focussed on the analysis of stopwatch TPN's (SwTPN's) and proposed and implemented two techniques for analyzing their state spaces: a semi-algorithm building exact representations of their behavior and a new over-approximation method – based on a quantization of the polyhedra representing temporal information – yielding finite abstractions for a subclass of bounded SwTPN's.

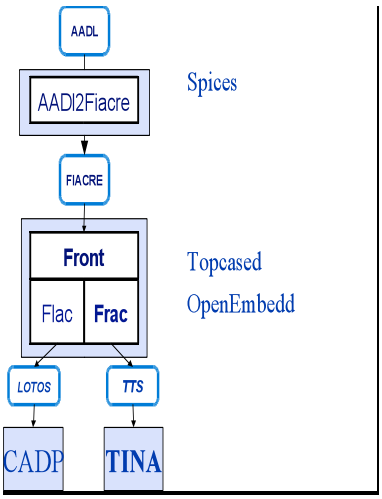

Figure 1. Verification chain from AADL to TINA

"Tooling" — To validate our models and the associated model-checking algorithms, we develop the TINA toolbox (Time Petri Net Analyzer) [INV 40, OS43, OS45]. Over the last period, supports for the different proposed extensions of TPN's have been integrated into the TINA toolbox allowing the edition, animation and formal verification of these models. Another tool, POLA, has been designed that allows analyses by TINA of scheduled systems from their descriptions in a DSL (Domain Specific Language) [ACTN311].

"Experiments" — To integrate our research results within the framework of systems engineering and to evaluate our tools, we participate to the [Topcased] AE/SE project and to the ANR platform [OpenEmbedd, ACTN339]. TINA is one of the two – with CADP – target verification engines of these projects. A Fiacre compiler (Front/Frac) has been developed to allow the verification using TINA of Fiacre description. In complement to these projects [ACTI1506], collaboration with IRIT in the [SPICES] project resulted in a complete verification chain - from AADL as user formalism to TINA, through the intermediate language Fiacre. Other experiments, in collaboration with IRIT and UFSC [SCTR, Tapioca], are concerned with the integration of model-checking techniques in a model-driven engineering approach [ACTI1148, OS61, ACTI783]

Communication, Architectures and Protocols

Our research aims at designing protocols and architectures for next generation networks.

This means considering current ***constraints*** related to such networks: *quality of service (QoS)* and *security* in *heterogeneous* networks, especially *wireless and mobile networks*

In such a context, the ***goal*** is to design new *adaptability* mechanisms to the environment, and which completely hide the different network technologies encountered on the communication paths. The network would be *ubiquitous* and *seamless*. The ultimate goal is to make the network *autonomic.*

Methods for reaching this goal rely on the development of new architectures, *model oriented design*, *validation* and *performance evaluation* techniques.

For this purpose, we rely on the use of *simulation*, *emulation* as well as network *monitoring and measurement* techniques and tools [ACLN 36, ACTI126]. In addition, a big effort has been provided for creating *experimentation platforms* for testing our proposals (see section on the LaasNetExp platform) [ACTI7644].

During the last four years, our main research topics dealt with:

- Access networks architectures, which are more and more numerous, and different, more and more often wireless and mobile. We especially focused on wireless local area networks (WLAN) [ACTI1476, ACTI1279, ACTI1310, ACTI1452], satellites networks [ACL95, ACTI 1072, ACL264] and sensor networks [ACTI1013, ACTI1032].
- Networks and services integration architectures, based on the use of the network virtualization concept, and signalling in virtual networks. It was especially developed in the EuQoS project (fig. 1) [DO 19]. In the EuQoS project, some contributions also dealt with network, QoS, and traffic monitoring [ACL10, ACTI4256].

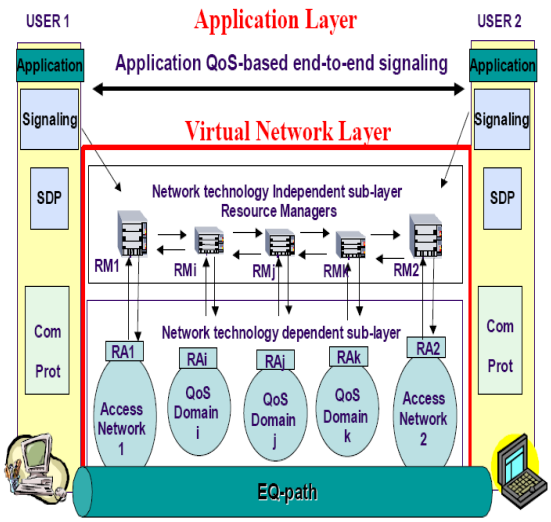

Figure 2. The EuQoS signalling architecture in a virtual network

- End-to-end dynamic and self-adaptative communication architectures, i.e. able to adapt to the current environment [ACL210, ACL463].
- Security, and more specifically traffic anomalies detection. The goal was to avoid QoS to be degraded when denial of service (DoS) attacks or flash crowds arise [ACTI285]. The original contribution relies on the use of a non Gaussian and long range dependent model of the traffic which works for both normal traffic and traffic with anomalies, and makes possible to distinguish between legitimate and illegitimate anomalies [MétroSec, ECODE, COST TMA, ACL382]. We also worked on studying malicious traffic. For this purpose, a specific platform consisting of honeypots for collecting malware (viruses, worms, …), sand boxes for executing malware in a protected environment, DNS servers for routing outgoing malicious traffic towards our protected environment, and a new multi-levels firewall for detecting dangerous outgoing traffic and blocking it in order not to corrupt distant hosts [OSCAR, ACLN 50].
- Experimental evaluation techniques and tools relying on emulating realistic networks and traffic, and on the monitoring and measurement of networks, their traffic and their services. It led to de design and building of an experimental platform allowing simulation, emulation and experimentation in real environments. This platform, named LaasNetExpt (LAAS NETwork EXPerimentation) consists of around 50 versatile machines, monitoring equipments, switches, routers, 7 terminals, and a screen wall for visualizing running experiments [ACTI7644]. Realistic traffic generators were also developed [MétroSec].

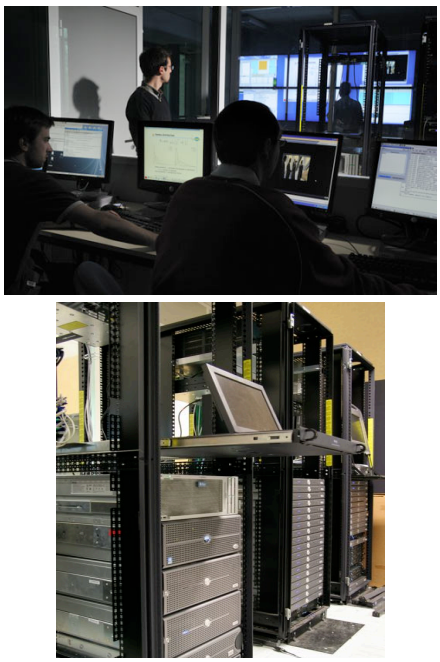

Figure 3. The LaasNetExp experimental platform

Services and Components for Coooperation

The objective of the theme SCC is to design self-configuring cooperative communicating services that are able to adapt autonomously their behavior in a proactive or reactive way. This is necessary to handle the variation of the infrastructure constraints (communication and execution resources) and the evolution of the requirements of the application level.

The scientific topics include:

- Homogeneous design of dynamically reconfigurable architectures for the multiple levels of the software stack hosted by the execution nodes. This includes group communication protocols and event-oriented group communication at the middleware level [ACTI573, ACTI999]
- Handling the consistency of reconfiguration between the different levels of communication and cooperation and the continuity of reconfiguration between the deployment nodes [ACL472, ACTI557].
- Description and dynamic discovery, selection and deployment of the cooperation services and their components [ACL326, ACTI744].
- Defining and experimenting dynamic priority mechanisms for message scheduling in Networked Control Systems [ACTI496, ACTI1189].

Our work in the last four years aimed at designing, modeling and implementing the enforcement architectures and the analysis models providing model-based cooperative and coordinated multi-level adaptation solutions in the general context of group communication.

The approach elaborated relies on the distributed and multilevel (cross-layer) adaptability in a coordinated and dynamic way. It acts during runtime on the end-to-end protocols with dynamic architectures, in particular the transport [ACTI714] and the upper communication levels [ACTI816, ACL485]. It makes it possible to adapt QoS to the evolution of the application-level requirements and the variation of the communication constraints.

Our approach of managing the multi-level adaptation by model-driven and rule-oriented dynamic architectural reconfiguration allows correct by design solutions to be built. This is important for the considered scope of critical applications [ROSACE], and for mastering model complexity in the heterogeneous network and devices context [NETQOS, USENET] and for scalability guarantee.

The **contributions** of the last period include:

- Developing reconfiguration models for each communication level and transformation models mapping the architecture of a given level on the architecture of another level [ACL472]. Our models are defined using tractable notations appropriate for describing dynamic architectures and provided with a formal semantics allowing proof development [ACL198].
- Developing reconfiguration policies implementing high level objectives of the type: co-operative or hierarchical management of communication resources. This work has been conducted in collaboration with APC theme in the context of NetQoS project [ACTI1299, ACL590, ACTI541].
- Implementing and experimenting, in the most advanced technologies and in conformance to the reference standards [ACTI1334].

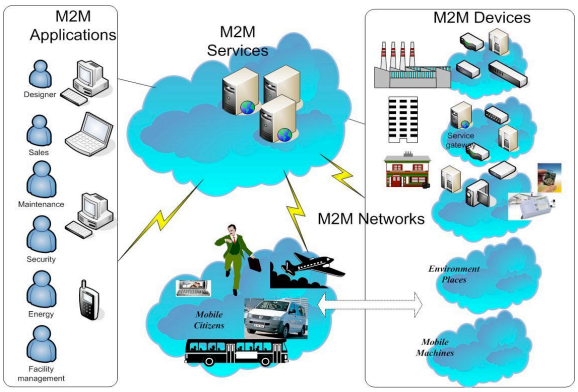

Figure 4. The Usenet project platform

In the context of R&D and collaboration projects, supporting these studies, we experimented and validated our solutions by various scenarios and in various application domains. We addressed communication and cooperation support applications with strong constraints of interaction and strong requirements for dynamic reconfiguration: crisis management operations, information sharing and collaborative distributed e-activities [ACL521]. We applied our solutions to various architectural styles: C/S, P/C, P2P, and with various software technologies: distributed objects and components, Web-Service [WS-DIAMOND, OS79, ACTI1284, ACTI853], M2M [USENET].

Significant projects and collaborations

Projects

[MétroSec] Metrology for Security and QoS, ANR ACI 09/2004 -36 mois, http://www.laas.fr/METROSEC

[OSCAR] Overlay network Security: Characterization, Analysis and Recovery (RNRT, 04/2006, 04/2008)

[COST-TMA] Traffic Monitoring and Analysis (FP7, COST Action, started September 2008)

[ROSACE] RObots et Systèmes Auto-adaptatifs Communiquants Embarqués, RTRA, 09/2007, 48 mois, http://www.laas.fr/~khalil/ROSACE/

[**USENET**] Ubiquitous M2M Service Networks ITEA2, 09/2007 - 42 mois, http://usenet.erve.vtt.fi/

[EuQos] End-to-end Quality of Service over heterogeneous networks (FP6 IST IP - 09/2004-12/2007 www.euqos.eu)

[WS-DIAMOND] Web Services – DIAgnosability, Monitoring and Diagnosis (FP6 IST FET 09/2005- 09/2008 http://wsdiamond.di.unito.it)

[Safe_Necs] Safe-Networked Control Systems ANR - ARA - SSEIA 01/2006 - 36 mois http://safe-necs.cran.uhp-nancy.fr/

[SPICES] Support for Predictable Integration of mission Critical Embedded Systems ITEA 09/2006 - 36 mois http://www.spices-itea.org

[OpenEmbeDD] Model Driven Engineering open-source platform for Real-Time & Embedded systems - RNTL (Plateforme) 03/2006 - 36 mois - http://openembedd.org

[Topcased] Toolkit in OPen-source for Critical Application SystEms Development DGE + CRMIP - Pôle AE/SE 08/2006 - 60 mois www.topcased.org

[NetQoS] Policy Based Management of Heterogeneous Networks for Guaranteed QoS, FP6 IST STREP, 05/2006 - 30 mois http://www.netqos.eu/

Collaborations

[CNRS-WIDE] Collaboration between CNRS and Japanese WIDE institution on network monitoring, network security and wireless

networks, CNRS and JST, 01/2006 36 mois, http://cnrs.wide.ad.jp/

[CSTR] Conception de Systèmes Temps Réel Répartis, CAPES-COFECUB 01/2004 - 24 mois http://www.laas.fr/LAAS-UFSC/

[MC3] Modèles de Coopération, Coordination et Communication appliqués au cas d'une Chaine d'Approvisionnement, CAPES-COFECUB, 01/2003- 60 mois http://www.laas.fr/~khalil/MC3

[Tapioca] Timing Analysis and Program Implementation on Complex Architectures CNRS Stic-AMSUD 01/2008 - 36 mois http://www-verimag.imag.fr/~yovine/projects/tapioca/

[TENEMO] Télé-NEuroScience sur une plateforme collaborative Mobile sur Internet. Projet Volubilis, 01/2008 36 mois, http://www.laas.fr/~khalil/TENEMO

[SWGCI] Services Web pour la Gestion Coopérative de l'Information Partagée. Projet CMCU N° : 05G 1409, 05/2005-36 mois http://www.laas.fr/~khalil/SWGCI

Tools

Fiacre http://gforge.enseeiht.fr/projects/fiacre

TINA http://www.laas.fr/tina

Main facts

- **Project EuQoS:** "End-to-end Quality of Service over heterogeneous networks" IP FP6 IST. As an achievement of the project, the book [DO19] has been issued and is distributed world-wide.
- Complete verification chain from AADL to TINA.
- 22 PhD &7 HDR defunded during the period, 5 new researchers, 2 retirements, 2 delegations.
- **Chairing of PC/TPC/Organization :** Algotel'05, E2EMON'05, CoNEXT'05, HPCC'2006, ICISP'06, NOTERE' 06, MonAM'07, FET'2007, MWCN'2008, QSWS'08, SARSSI'08, WEB2T' 08, PWC'2008, ICCC'2009, COST-TMA'09, SHWS'09, WEB2T'09, SARSSI'09, FET'2009, RESCOM'06..09
- **Best Paper awards:** ECSA'07 [ACTI931], ADVCOMP'08 [ACTI1272], ICEIS'07 [ACTI783]
- **Award Léopold Escande (INPT):** T. Rakotoarivélo PhD Thesis NICTA Sidney/LAAS 2007.

Dependable Computing and Fault Tolerance – TSF –

Permanent Staff:

Members: J. Arlat (DR), J. Collet (DR), A. Costes (P), Y. Crouzet (CR HdR), A. de Bonneval (MC), Y. Deswarte (DR), J.C. Fabre (P), J. Guiochet (MC), M. Kaâniche (DR), K. Kanoun (DR), M.O. Killijian (CR), J.C. Laprie (DR), V. Nicomette (MC), D. Powell (DR), N. Rivière (MC), M. Roy (CR), P. Thévenod-Fosse (DR), H. Waeselynck (CR)

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Long term visitor: A. Louri

Objectives and positioning

The work of the group focuses on the dependability of computing systems, i.e., the ability to deliver a service that can be justifiably trusted. It encompasses the properties of availability, reliability, integrity, confidentiality, maintainability, safety, as well as security.

Our research covers design, testing and evaluation activities. A strong characteristic of our research is the scope of the faults addressed: physical faults, software faults and malicious interaction faults, i.e., intrusions. Moreover, for many years the group has conducted both conceptual and experimental work. The resulting depth and breadth of our research has given our group a prominent position within the dependable computing community.

In France, these various topics are addressed by several other groups (e.g., see IRISA, LaBRI, CEA-LIST, TIMA, LIRMM, Vérimag), but not with the same overall coverage. Internationally, the group may be compared to: the Dependability Group at the University of Newcastle, UK, the Dependable Computing Research Lab. at ISTI-CNR in Pisa, Italy, and the Center for Reliable and High-performance Computing at the University of Illinois at Urbana-Champaign, USA.

Highlights and Major Achievements

Our research, which is upheld by the formulation of the basic concepts of dependable computing, covers four themes:

- Fault prevention: how to prevent the occurrence or introduction of faults.
- Fault tolerance: how to provide service delivery in spite of faults.
- Fault removal: how to reduce the number or the severity of faults.
- Fault forecasting: how to estimate the creation, presence and consequences of faults.

The research topics covered during the reporting period are listed in Figure 1, and are detailed in the remainder of this section.

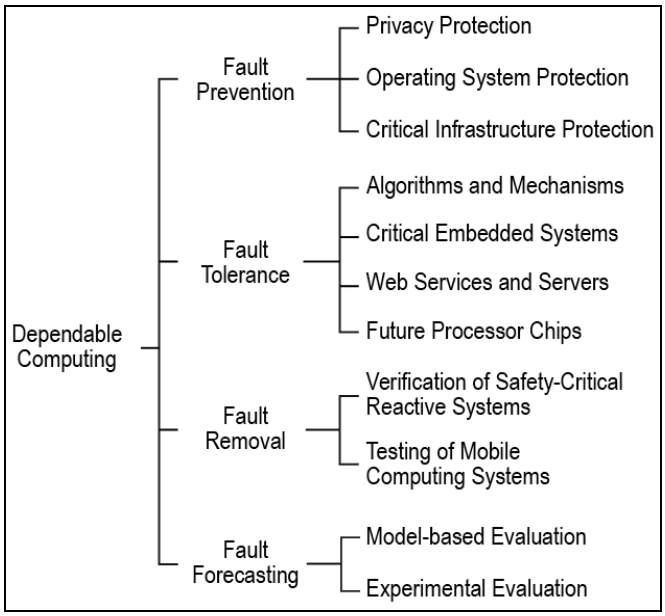

Figure 1: Research topics

Fault Prevention

Our research focuses on security aspects, i.e., preventing attacks from succeeding. Our main recent results concern privacy protection, operating system protection, and critical infrastructure protection.

"Privacy protection" — Privacy requires the development of: a) *authorization* schemes that can efficiently protect personal information, including that held on remote sites that are not under direct user control, and b) *means and mechanisms* that allow users to enforce their sovereignty on how their personal information is used. Concerning privacy-preserving authorization schemes, we apply an approach that we developed previously for securing applications distributed on the Internet, through which access control decisions are separated from access control enforcement. For efficiency, access control decisions are carried out at a coarse-granularity level (e.g., the level of a global transaction) so that decisions can be based on the semantics of requests, according to both the user's privacy policy and the server's security policy. To prevent malicious bypass, access control enforcement is done at each Personal Identifiable Information

access, according to authorization proofs delivered by the decision function [OS17].
Anonymizing personal data is an important problem, in particular for medical data, since such data is very sensitive, but also very useful for epidemiology and therapeutics research. The technique we developed consists in generating an anonymous identifier that enables all data relative to a particular patient to be linked together for a particular research project, even if it comes from several independent sources (doctors, hospital, etc.), while preventing any cross-correlation with data collected for other projects. The anonymous identifier is generated by a patient smartcard (such as the French *Carte Vitale*) so that the patient controls: a) the collection of the data and b) the disanonymizing process, when that is necessary [ACLN24].
We have also addressed the problem of anonymous communication, which is necessary to guarantee user privacy in networks where metadata such as IP addresses can identify all communications of a given user. The classical solution to this problem is to use anonymity relays (called MIXes), so that an observer cannot identify which user is communicating with whom. Such a solution induces transmission delays that are incompatible with new applications such as VoIP. By using various cryptographic techniques (DC-nets, ciphered padding, Private Information Retrieval), we have reduced the latency by creating a single relay that is as trustworthy as a chain of relays [ACTI1027, TH66].

"Operating systems protection" — Operating system kernels are often the main target of malevolent attacks since, if successful, such attacks give the attacker complete control of the computer. Since most existing operating system kernels are very complex, they are vulnerable to such attacks, and malicious hackers have developed many *rootkits* for this purpose. Through a detailed analysis of the way rootkit-based attacks access the kernel and then corrupt its address space, we have proposed a protection scheme for Linux that relies on a hardware-supported hypervisor (HyTux) that exploits the virtualization capabilities of the underlying CPU. HyTux is a lightweight hypervisor that implements protection mechanisms in a more privileged mode than that of the Linux kernel. As such, it cannot itself be bypassed by the possibly compromised kernel [ACTI1461].

"Critical infrastructure protection" — Critical infrastructures are managed by many organizations that interact with each other by interconnecting their information systems. Each information system is composed of logical/physical systems, has its own applications and access control policy, and proposes its services to other systems (see Figure 2). To address the security challenges raised by such infrastructures, we developed a collaborative access control framework called PolyOrBAC. This approach offers each organization the ability to collaborate with the others, while maintaining control of its own resources and internal security policy. The interactions between organizations are implemented through web services. For each web service, a contract is signed between the service provider organization and the service user organization. The contract describes the web service functions and parameters, the liability of each party and the security rules controlling the interactions. At runtime, the compliance of all interactions with these security rules is checked. Any deviation from the signed contract triggers an alarm. The concerned parties are notified and audits can be used as evidence for sanctioning the party responsible for the deviation [0S78].

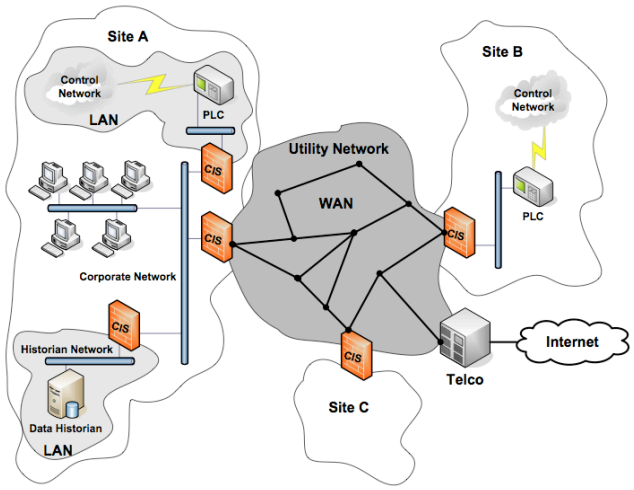

Figure 2: A Critical Information Infrastructure

Fault Tolerance

Our research on fault tolerance concerns the design of computer architectures able to tolerate a wide spectrum of faults (physical, design, and malicious faults). The principal results relate to: a) algorithms and mechanisms for real-time and adaptive fault-tolerance, b) architectural solutions for critical embedded systems, c) dependable and secure Internet services and servers, d) future processor chips able to cope with the issues raised by hardware technology downsizing.

"Algorithms and mechanisms" — Three topics have been addressed: timing error detection, and adaptation and resiliency techniques for dealing with dynamic system evolution.
Timing error detection is of utmost importance in systems that have to respect real-time constraints. We have defined a class of low-latency error detectors that can be automatically derived from formal models of the expected real-time behavior of software applications. These detectors check at run-time

whether the execution matches the specification. Our contributions are twofold [ACTI1393]. First, we have proposed a formal framework for the characterization of "early detectors", ensuring a predictable behavior of the detection system. Second, at a practical level, we have provided a description of the complete generation process, from the models to the code of the detector.

The *evolution of systems* during their operational lifetime is becoming a central issue for dependable systems. Such evolutions may be linked to the environment or the execution context. To match service delivery to the current operational conditions, it must be possible to tune the software configuration accordingly (i.e., software adaptation). This is true both for application services and fault tolerance services. Two main contributions have been made in this direction [ACTI1392, TH204]: a) the design of a reflective framework and open component-based software engineering techniques for dynamic adaption, b) a method for synchronizing adaptation while maintaining liveliness and safety properties.

Systems can also evolve dynamically due to the mobility of users and of their devices, or due to massive numbers of autonomous devices that constantly connect and disconnect, fail, etc. To handle the dynamics of such systems, cooperation-based peer-to-peer like approaches are attractive. We developed a set of middleware building blocks for the provision of resilient services for mobile systems: a proximity map, a trust and cooperation oracle, and a cooperative data backup service. [ACTI601, TH128].

"Critical embedded systems" — The main issues addressed in embedded systems have concerned the integrity of communications in embedded networks, the dependability of software for autonomous robots and the use of commercial off-the shelf (COTS) components.

The trend towards *digital communication networks* is a major mutation in critical control systems (e.g., in avionics). This trend encompasses also the sensor and actuator networks. To ensure the integrity of such communications, we have proposed an innovative protection technique based on the repeated application of distinct cyclic redundancy checksums, to minimize the risk of common mode failures [ACTI604, TH37, Patent AIRBUS/CNRS N° FR2878097, WO2006053956]. Our current work addresses the evolution of flight control systems towards more distributed architectures, which are able to transfer a significant share of the processing power towards "smart" sensors and actuators [ACL564].

Autonomous robots make extensive use of decisional mechanisms that are able to take complex and adaptive decisions, but are very hard to validate. Techniques for tolerating residual design faults are thus of real interest for critical robot applications [TH107]. With the RIS group, we have carried out two investigations in this direction. First, we designed, implemented and validated a temporal planner able to tolerate design faults in its declarative domain model and search heuristics [ACTI1793, ACTI937] (Figure 3). Second, we have set the foundations of "safety modes", a method for structuring real-time checking of safety constraints for multi-functional robots [ACTI1117, ACTI1326].

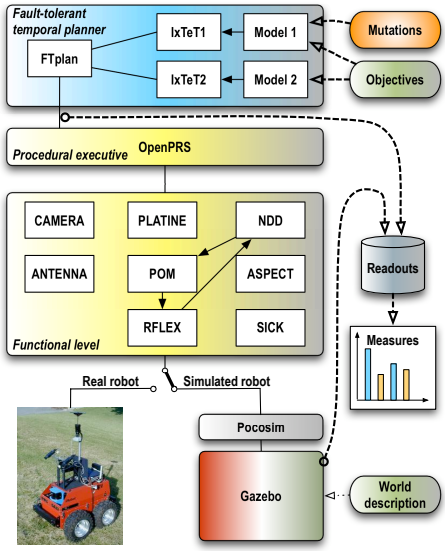

Figure 3: Fault-tolerant temporal planner and its validation by model mutation

The use of COTS components in, or in interaction with, critical embedded systems raises several dependability concerns.

First, the integration of such components in modular embedded software may give rise to errors if their interactions with other components are not rigorously controlled. Unlike most solutions that address errors locally within each component or report them to diagnosis services, we have proposed a global wrapping-based approach that provides runtime checking of multilevel properties in a complete, AUTOSAR-compliant, multilayered modular software architecture (kernel, middleware, application).

Second, the connection of standard COTS laptops to embedded computers (e.g., to facilitate maintenance operations on aircraft) poses serious security threats. Any errors resulting from malware affecting the laptop resources (especially the laptop operating system) must be prevented from impacting the on-board system. We have proposed a solution based on the *virtualization paradigm* to secure the execution of tasks on the laptop: at least two task instances, each running on a distinct software executive, are executed and compared [ACTI1430]. An attack targeting an

instance running on one executive would likely fail on the other, and would thus be detected.

"Internet services and servers" — Our research efforts have addressed both accidental faults and malicious intrusions. Service-oriented applications are large-scale distributed applications, and are typically highly dynamic and often unstable. Indeed, the underlying web services are very unreliable since they can be moved or deleted without notice, and are subject to various sources of failures. We have proposed customizable connectors (featuring executable assertions for detection, and replication strategies for recovery) to provide fault tolerance in the face of unreliable web services (Figure 4). The benefits of this approach were demonstrated experimentally [ACTI794, TH87].

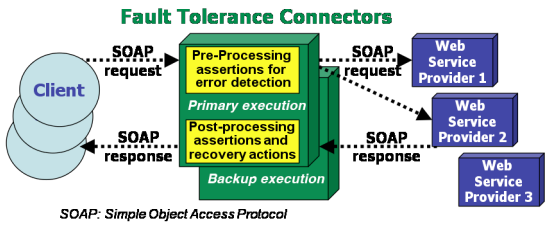

Figure 4: High-availability Web services

Conventional protection techniques are rather inefficient in protecting critical systems connected to the Internet from attacks. In this context also, redundancy and diversification principles can be used to provide fault tolerance. We have proposed a solution using redundant tolerance proxies that mediate client requests to a redundant bank of diversified COTS application servers [ACL559, TH2]. To improve performance, the proxies can adjust the level of redundancy level according to the current alert level.

"Future processor chips" — Future processor chips will increasingly feature very large-scale multi-core architectures. Due to technology downsizing towards nanometer dimensions, it is to be expected that some cores or interconnects be defective from the outset (resulting in reduced yield) and be more impacted by soft errors (e.g., SEU's) during operation. To address these issues, we have introduced a new self-configuration methodology that allows defective cores to be detected, isolated and deactivated, and communications and tasks to be reconfigured and reallocated (Figure 5) [ACTI904]. The efficiency of the methods has been studied as a function of the fraction of defective cores, defective interconnects and soft error rate [ACTI1217, TH168].

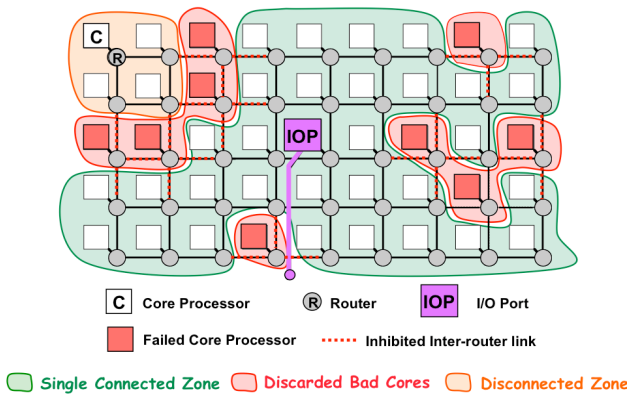

Figure 5: Typical multi-core topology and interconnection

Fault Removal

Our major results in fault removal concern the verification of safety-critical reactive systems and the testing of mobile systems.

"Verification of safety-critical reactive systems" Our work on the verification of safety-critical reactive systems is applied to avionics systems. Two directions have been explored.

The first one concerns the definition of test cases at a higher level of abstraction than what is typically done with current test script languages. The principle is to have declarative and generic test-case descriptions that capture the intent of the tester and can be specialized to different implementation contexts. The descriptions can cover the activation part of a test, or the oracle part in charge of establishing a pass/fail verdict. So far, our work has focused on the oracle part. We have defined a solution based on the Lustre language [ACTI1300]. The specified oracle checks accommodate (a) comparison to expected results with some tolerance in the time and value domains, and (b) more general properties relating inputs and outputs. They can be instantiated for several concrete tests. The approach has been successfully applied to industrial examples.

The second direction concerns the formal verification of detailed design models used for automated code generation. Currently, the industrial practice is to test the models in a simulated environment. Our work considers the introduction of model-checking. From our analysis of cases extracted from flight control systems, a key issue concerns the exploitation of counterexamples showing property violation [ACTI1460]. To address this issue, we have proposed an automated structural analysis technique that identifies parts of the model that are activated by a counterexample over time. This analysis allows us to extract relevant information to explain the observed violation, hence facilitating its interpretation. It also serves to guide the model-checker toward the

exploration of different violation patterns (i.e., exhibiting different activation patterns), if needed.

"Testing of mobile computing systems" — To address the testing of applications and services in mobile computing systems, we have first considered a fundamental conceptual problem: how to express interaction scenarios between mobile nodes. Scenarios are useful to represent various test artifacts (Figure 6), but existing languages are not sufficient to account for mobile settings [ACTI872]. We have proposed extensions, including the introduction of a spatial view using labeled graphs, to describe the topological system configurations. We exemplified the introduction of these extensions into UML sequence diagrams. With the spatial view, the analysis of test traces against scenarios now involves graph-matching. We developed an algorithm to reason about sequences of graphs, allowing us to determine which physical nodes appearing in a trace can match the successive configuration patterns appearing in a scenario. The graph analysis can then be supplemented by an analysis of the ordering of communication events, which was exemplified by taking an automata-based semantics.

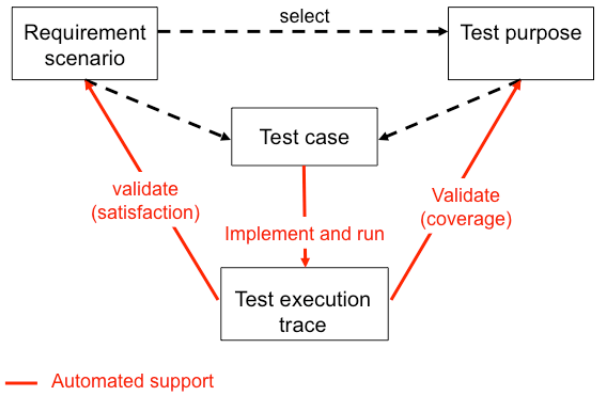

Figure 6: Role of scenarios from a testing perspective

Fault Forecasting

Our activities concern model-based evaluation and experimental evaluation of the consequences on dependability of accidental physical faults, accidental design faults, and malicious threats.

"Model-based evaluation" — The objective is to develop probabilistic models to support design decisions and to analyze and quantify the impact of faults on dependability. A major challenge is to capture the main phenomena inherent to the target application that have a significant impact on the dependability measures of interest (impact of accidental and malicious faults, interdependencies, mobility, etc.), and to master model complexity.

The first topic concerns the establishment of a link between architecture description languages, in particular AADL (Architecture Analysis and Design Language), and stochastic Petri nets to facilitate the quantitative analysis of dependable architectures. We developed a modeling framework including reusable modeling patterns for fault-tolerant architectures [OS38], and an automatic model transformation tool, ADAPT, allowing the generation of Generalized stochastic Petri nets from AADL models [ACTI1120]. This framework was illustrated on a subsystem of the French Air Traffic Control system [TH129].

The second topic addresses the dependability modeling and evaluation of distributed applications implemented on mobile devices using ad-hoc networks. The main challenge concerns the quantification of dependability characteristics taking into account the combined effects of faults affecting the mobile nodes and their communication, and the mobility of these nodes. The proposed models are based on stochastic Petri nets and Stochastic Activity Networks (SAN). Also, simulations have been performed to estimate some connectivity characteristics in dynamic mobile scenarios, in particular for vehicular applications. Three case studies have been investigated: a) a distributed application using cooperative backups on mobile nodes (Figure 7) [ACTI1019], b) a replication service for applications running on ad-hoc networks [ACTI1118], and c) an automated highway system based on platooning [ACTI1531].

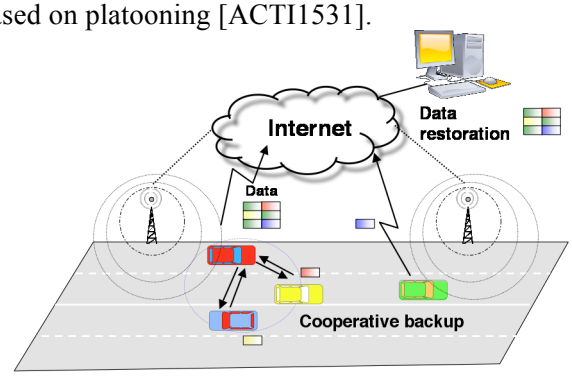

Figure 7: Cooperative backup on mobile devices using ad-hoc networks (automobile context)

Traditionally, model-based evaluation approaches take into account accidental faults only. Quantification is challenging when considering malicious threats. Our current investigations on this topic focus on system vulnerabilities caused by design and implementation errors, and on how the system environment, considering such vulnerabilities, may endanger the system. The proposed approach is based on: a) the identification of the environmental factors that influence the system security state (vulnerability lifecycle, attack profile, administrator behavior); b) the development of a SAN model taking into account both the system and these environmental factors. The quantitative measures obtained from the model aim to help the system

designers in the assessment of vulnerability exploitation risks [ACTI1140].

Beyond computer systems and their applications, we have undertook modeling *interdependencies of critical infrastructures*, namely the electricity and informational infrastructures. Interdependencies are being increased by recent evolutions in electricity infrastructure control and monitoring architectures and operations, due to the opening of these architectures to allow market deregulation and competition. We have produced a model of failures resulting from interdependencies, enabling a unified representation of the influence of accidental and malicious threats. The model is based on the assumption that cascading failures originating from malfunctions in a given infrastructure induce constraints on the other infrastructure (e.g., performance degradations or inappropriate human actions), leading to so-called escalating failures. A state-machine model describes in a compact form the behavior and interdependencies of the infrastructures. The model is made explicit by a stochastic Petri net evidencing the phenomena leading to cascading and escalating failures. This is the first published unified model of infrastructure interdependencies [ACTI902].

"Experimental evaluation" — Two main topics have been investigated. The first topic focuses on the development of benchmarks of dependable computing systems. The second one deals with experimental evaluation activities targeting malicious attacks and intrusions.

Our work related to *dependability benchmarking* aims to assess the robustness of an operating system (OS) with respect to application failures that result in erroneous requests to the services of the OS at the API level (Application Programming Interface) [OS59] or the system calls via the interface of the drivers [OS56, ACL511, TH11]. Besides traditional robustness measures, the specification of the proposed benchmark also includes timing aspects. We have developed a testbed framework suitable for OS dependability characterization. The framework was first used to compare the reliability of three generations of the Windows family (NT4, 2000 and XP). It was extended to evaluate instances of the Linux family [TH 15].

Systematic evaluation approaches are also needed to provide better protection with respect to malicious threats. This requires: a) the identification of realistic attacks that may affect the target systems and, b) the development of a rigorous evaluation approach to assess the efficiency of the protection mechanisms in coping with potential attacks.

The first objective is covered by our experimental work on the collection and analysis of real-life attack data, based on honeypots (Figure 8). The first contribution concerned the elaboration of statistical models characterizing the attack processes observed on a large set of low-interaction honeypots deployed at various geographic locations on the Internet, in the context of the Leurré.com platform administrated by Eurecom. Such honeypots emulate simple services and cannot be compromised by the attackers. The second contribution concerned the development and deployment of a high-interaction honeypot that offers a more suitable environment for observing the progression of an attack within a system, considering as an example intrusions carried out though the ssh service. The data collected during a nine-month deployment period allowed us to observe different stages of real intrusions and to validate the relevance of our approach [ACTI602, TH146].

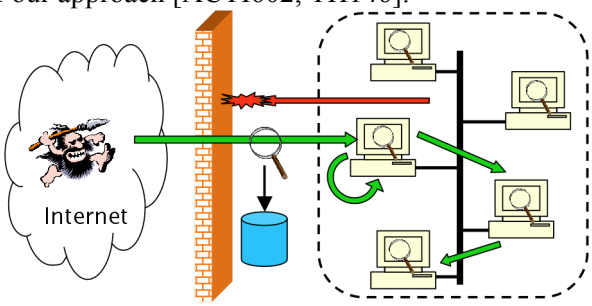

Figure 8: Honeypots: Observation of Internet attacks

As regards the *evaluation of security protection mechanisms*, our current research focuses on intrusion detection systems (IDS). We have proposed a model-driven approach and a tool to run evaluations in a systematic way. This approach is based on a new classification of attack activities with respect to IDS-relevant manifestations or features that exhibits the dynamics of the attack process. It results from the analysis of a large number of attack incidents and malware samples, including the data collected from our honeypots. To implement this approach, we have designed a flexible evaluation tool based on the Metasploit framework that provides attack injection as well as background traffic generation. The feasibility and the flexibility of the proposed approach for the systematic generation of evaluation test cases have been illustrated on two different IDS's (*Snort* and *Bro*). [ACTI 974, TH201].

Significant projects and collaborations

Our research activities are exemplified via tools and demonstrators (see Table 1). They are implemented and exploited within several cooperative projects as shown in Table 2 that presents the main projects that have been running during the reporting period. This table reveals our strong implication in cooperative programs both in Europe and in France.

Besides the cooperation within projects, the group has long-term cooperation with several institutions such as

with the University of Illinois at Urbana Champaign (USA), the SEI at Carnegie Mellon University (USA), UniCamp (Brazil), and Lancaster University (UK). The group has also co-advised doctorate theses with colleagues from IRIT, Budapest University of Technology and Economics, ONERA, and the University of Lotz (Poland).

Additional salient facts

In addition to the very significant results presented, we want to highlight three facts not yet mentioned:

• The coordination and the completion of the ReSIST European Network of Excellence, which gathered 105 researchers and 68 doctoral students, from 14 academic institutions and 4 industrial companies, from 8 countries. Besides the successful integration of the participants, and the many scientific results, the training activity is worth being emphasized, as it led to the definition of a Master of Science curriculum in Resilient Computing, and of the production of an associated courseware. The latter includes 1590 lecture slides, among which 477 are from LAAS. The curriculum and the courseware are freely available on the ReSIST website (http://www.resist-noe.eu). They are the first multi-national, collaborative, sources available to organisers and providers of courses in Dependable and Secure Computing.

• The publication in 2008 of the first book on Dependability Benchmarking for Computer Systems, coordinated by LAAS and IBM. Its sixteen chapters have been worldwide contributed by seven academic institutions as well as by six industrial companies (out of which IBM, Intel, Microsoft, Sun Microsystems). The book has been hailed as a milestone in dependability assessment.

• The winning by Jean-Claude Laprie of the 2009 Grand Prize in Informatics of the French Academy of Sciences.

Table 1: Tools and demonstrators

Acronym	Description
ADAPT	From AADL Architectural Models to Stochastic Petri Nets via Model Transformation
ARUM	Scaled-down Platform for Experimental Evaluation of Mobile Systems
PRIM'Air	Demonstrator of an Airline Web Service featuring the PRIME Security and Privacy Mechanisms
GraphSeq	Graph Matching Tool for Sequences of Spatial Configurations
PHi	High Interaction Honeypot for Intrusion Analysis

Table 2: Cooperative projects

Funding	Acronym	Topic	Period
EU	PRIME	Privacy and Identity Management for Europe (Integrated Project, IP)	03/04-05/08
	ASSERT	Automated proof based System & Software Engineering for Real-Time applications (IP)	09/04-02/06
	PHRIDOM	Physical Human Robot-Interaction in Anthropic Domains: Safety and Dependability	04/05-02/06
	ReSIST	Resilience for Survivability in IST (Network of Excellence)	01/06-03/09
	HIDENETS	Highly Dependable IP-based Networks and Services	01/06-03/09
	CRUTIAL	CRitical UTility InfrastructurAL resilience	01/06-03/09
	PHRIENDS	Physical Human-Robot Interaction: Dependability and Safety	10/06-09/09
ANR	CADHo	Collection and Analysis of Data based on Honeypots	10/04-09/07
	MoSAIC	Mobile System Availability, Integrity and Confidentiality	10/04-09/07
	MASCOTTE	Mastering and Control of Execution Times	01/06-12/08
	SCARLET	Critical Automotive Systems: Robustness of Real Time Software Executives	03/07-02/10
	MIRAS	Multimodal Interactive Robot of Assistance in Strolling	01/09-06/12
	DALI	Design and Assessment of application Level Intrusion detection systems	01/09-12/11
FNRAE	MARAE	Methods and Robust Architecture for Autonomy in Space	01/08-12/10
EADS-IW	—	Securing COTS-based Computer Systems	11/06-10/09
Airbus	—	Test automation	01/06-12/07
EADS-Astrium	—	Online Safety Monitoring Using Safety Modes	09/06-02/08
Airbus		Innovative Architectures for Flight Control Systems	01/07-04/10
Renault	—	Robustness of Real Time Software Executives	03/07-02/10
Airbus	—	Verification of Flight Control Systems	10/06-09/09
SDC/Airbus	GEODESIE	Safety and Security of Mobile Equipments Linked to the On-board Information System	07/08-12/11

System Engineering and Integration – ISI –

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Objectives and positioning

The development of more and more complex systems does come with a growing interest for System Engineering which targets process control to conform with all the requirements expressed. In a very constrained context, prompt and faultless design is required, while ensuring a design quality in compliance with existing standards. To meet these requirements means, on the one hand, progressing in the production of more and more methods and tools for complex system design, and on the other hand, developing System Engineering processes allowing the control of this design.

The ISI group stands in this context of design of complex systems, which can be components of bigger systems in embedded applications in the fields of aeronautics, automotive and railway industry, and microsystems. The systems considered, heterogenous by their very nature, are characterized by digital and analog functions, sensors, and actuators from various technologies.

The ISI group contributions aim to make easier the design of complex systems by improving development life-cycle processes, particularly requirement management, modeling, model integration, verification and validation, simulation and virtual prototyping, in a process, method and tool vision. The uniqueness of the ISI group's work is linked to its members' will to adapt the processes and models to heterogenous systems. The study of heterogenous systems requires a better communication between the different communities, for instance as an information and model exchange gateway.

In this field, there exist propositions, but they are insufficient. For example, the ISO[1] AP-233 for data exchange in System Engineering and for tools interoperability, or INCOSE[2] and OMG[3] in their combined effort to extend UML[4] to System Engineering (SysML[5] results from it). Deficiencies remain with regards to approaches, methods, and models, which allow verification and validation (V&V) of consistency between the different points of view, and more generally the V&V possibilities of the system properties.

Our work is divided into two axes, **system design and evaluation**. The first stream concerns requirement management, architectural and detailed design processes. The second one concerns the validation and verification of the system according to two complementary approaches, formal validation of system properties and simulation.

At the European and international level, our collaborations led to joint publications with foreign laboratories (Canada, USA, Australia, Germany, Portugal, The Netherlands, Colombia) and to the submission of four European projects of the PCRD type, three of which IP (*Integrated Program*) were unfortunately not accepted. We had exchanges for doctoral students and permanents in the universities of Montreal, Carnegie Mellon, UTS Sydney, Bremen, Aarhus, and Copenhagen in Denmark, Macao (China), and the University of the Andes, Bogota (Colombia).

Work on requirements engineering process has been conducted at the *centre de recherche d'informatique de la Sorbonne*, the INRA of Nantes, the RE@UTS group at the University of Technology of Sydney, the London Open University, and the University of Toronto. The originality of our work is based on the integration of requirements process within the frame of System Engineering, along with the analysis of the requirement evolution impact on the system security.

Regarding model integration including UML, the work performed particularly in the University of Southern California is based on model heterogeneity, but it is restricted only to computer science domain. Our work aims to take into account multi-model and multi-business aspects.

Moreover, solutions such as the new profile SysML which incorporates the AP-233 standard are proposed by OMG (*System Engineering and UML/MDA*) work teams.

Our work is complementary to that of these groups, and seeks to extend UML to formal techniques. UML associations to B and Z methods, treated in LIFC, LORIA, CNAM, INRETS, and in Southampton, Berlin or Lisbon laboratories report to the same thinking pattern. As far as we are concerned, the difference lies in the formal models

[1] ISO: International Organization for Standardization
[2] INCOSE: International Council On Systems Engineering
[3] OMG: Object Management Group
[4] UML: Unified Modeling Language
[5] SysML: System Modeling Language

considered, Petri Nets (PN) and Differential-Algebraic Equations (DAEs) [ACLN5] [ACLN7].
On dynamic hybrid system safety, Dugan's work (University of Virginia) focuses on dynamic fault trees introducing temporal gates and procedures for the computation of the probability of feared events. French AltaRica (IRCyNN, LABRI, ONERA, and industrial) and European ESACS (LABRI, ONERA and industrial) projects revolve around the use of classical discrete dynamical models (PN, automata, ...) in order to extract trees or sequences leading to a feared event. Our address of the issue is complementary as regards the models used and the expected results. Our approach is based on PN and linear logic modeling. As for results, a systematic search approach for critical scenarios in the case of embedded systems or dynamic hybrid systems was developed [ACTI166].
Finally, in the field of simulation, our concern is, on the one hand, uncertainty evaluation introduced by simulation and simulation validity, and on the other hand, distributed simulation based on HLA techniques. Simulation validity evaluation is a major issue when system simulation is used in early-stage identification of needs and requirements to validate specifications, which is the required minimum preliminary to design process. So is the case in the field of aviation manufacturing, which aspires to use it to support system certification. With the SVA project, the ISI group is a pioneer in the field.
The system simulation community works extensively on HLA techniques, which is a high-level architecture proposed by the DMSO[6], pushed by the DoD. HLA is based on the hypothesis that no simulation can meet all the needs. The objective of this architecture is to reduce modeling and simulation costs, by facilitating the reuse of elementary simulators and interoperability between distributed simulators.
Most of American and European industrial and laboratory work use HLA as a means of system validation/verification. Our approach departs from the work of DMSO in that it is necessary to couple simulation to formal approaches in order to use it as a complement of formal verification. We think it should be applied to upstream models, and thus as an anticipation of performance measurement or personnel training, even before the final product realization. Moreover, simulation quality is seen by the whole community in terms of accuracy and credibility; see the work of *Faculty of the Aerospace Engineering of the Delft University of technology,* or that of ONERA. We study it through the lens of uncertainty and uncertainty measurement compared to reality, specified in accordance with the simulation process stakeholders.

Highlights and Major Achievements

Heterogenous system design

The objective of this work is to control complex system modeling throughout the design process, but also in the very early stages of the life-cycle in order to validate and verify the system to be designed. The objective of our contribution, in compliance with that of the System Engineering community, is to obtain a rupture-free design flow in order to minimize the costs of realization, integration, validation, operation, and maintenance phases. This vision of system design leads naturally to a **design process** oriented work (modeling, model integration). Studies on model integration rely on instances, models, and meta-models; this leads us to a three-level structure: an object and/or function level, a component-oriented model level, and a level for direct expression of basic models (object level) into meta-models (UML, ADL, or HLA) [ACL81] [ACTI106].
We defined a design methodology implementing the EIA-632 standard (System Engineering standard) guidelines, which cover the whole design process, from taking the requirements into account to defining a logical solution. This approach builds on the integration of UML notation and PN. The main objective of these two models' integration is to facilitate the V&V of the system in study.
The validation of each stage of the design process builds on model transformation (UML sequence diagrams into PNs [ACTI610], then PNs into VHDL-AMS). Our model transformation approach uses meta-modeling for the description of transformation rules. This methodology was applied in the internal project LAAS "MOCAS", supported by HILES, a tool developed by the LAAS (ISI and N2IS groups) and the University of the Andes (Colombia).
This work on model transformation received positive feedback within the TOPCASED project, specially at WP5 (Model Transformation) and WP2 (Means of Model Development) levels.
SysML brings about new elements for system description. We therefore started our work with the aim of improving our design methodology by operating requirement diagrams as well as internal blocks diagrams. The latter make the component approach of our methodology easier. This methodology evolution relies on a renewed collaboration with the University of the Andes (Carlos Ernesto Gomez-Cardenas' Master dissertation). The method is being applied on an embedded system of a "vehicle remote opening" type.

[6] DMSO: *Defense Modeling and Simulation Office*

"Requirement and system property validation" — System validation activity has been addressed through two model types: requirement models (capture phase) and architecture models, both being expressed in SysML. Two aspects of this validation were studied. The first aspect concerns the system's static properties. The requirements are validated on SysML models in a formal way thanks to Object Constraint Language (OCL). The second aspect focuses on the system's dynamic properties. Requirements related to these properties have been validated by simulation, with the transformation of SysML blocks and the equations they contain into VHDL-AMS. The transformation has been done at the meta-model level on an Eclipse Platform and the OpenArchitectureWare tool. The models have been built based on the problem of an aircraft door with strong multidisciplinary and multibusiness charateristics, specially linked to mechanics and electronics [ACTI 1338, ACL 17, ACL 490]

System evaluation

"Search for critical scenarios" — Our approach for search of critical scenarios is an assistance to design; it allows the verification of a logical solution validity relative to the requirements for safe operation. The qualitative findings obtained with the ESA-PN tool [ACT1607] are completed with a quantitative analysis by simulation. The uniqueness of this work lies in that it tries to get around the problem of combinatory explosion and avoid the enumeration of states, and on the other hand, in that it proposes a method applicable to dynamic hybrid systems.
Monte Carlo simulation is used to refine the qualitative results in order to quantify the probability of occurence of identified feared events. Thanks to the first qualitative phase of the scenario determination, the Monte Carlo algorithm is optimized by forcing the randomly drawn histories and following the pre-identified scenarios, while correcting the resulting estimations. In its last version, the ESA-PN tool builds in the hybrid aspect, connecting to Matlab [ACTI290] [ACTI422] [ACTI527].

"Simulation-Virtual prototyping" — Our activity stands within a general framework of system evaluation by simulation. The objective of system evaluation is to ensure compliance with the different requirements at every stage of the life-cycle. It builds on various means for a better effectiveness and sufficiency of system validation and verification. These means are: search for model intrinsic properties and mapping with system properties, simulation, and virtual (and/or real) prototyping. System simulation and virtual prototyping processes are considered, at different abstraction levels and all life-cycle stages, as design support techniques and often start much earlier than the design cycle. Within the frame of simulation formalisation and the possibility to quantify findings, a simulation product must systematically specify three interlinked elements: an experimental setting, a reference model, and the model of the system to be simulated. This concept was used in one of our projects. Prototyping (real or virtual) will integrate the dynamics and performances of the surrounding systems in order to show an operating mode closer, or even identical, to reality. Ultimately, it will provide quick implementation solutions [ACT1291].
As for the evolution of models, tools and environments, the MDA approach, which allows to separate the model from its simulation context, was adopted. The problems addressed concern the processes, methods, and tools which make it possible to rely on simulation.
The following question reveals a hard spot. Given that there are many objects to a simulation, such as the behaviour and/or temporal model, the experimental setting, and the verification and validation context (V&V), how can consistency among these objects be ensured so that the resulting simulation model is the most representative and faithful? An approach is being developed and experimented with the SVA (Simulation Validation Assessment) project, conducted in partnership with the ONERA and AIRBUS-France (AIRSYS project).
For this purpose, the concept of abstraction and approximation as well as the model's intrinsic properties were used.
In this study, we worked on the link between the component approach used in software engineering and the simulation composition. The problem was addressed based on two approaches:

- The first approach is built around the concept of components and model integration by composition. We used the concept of virtual system, which consists in formalism encapsulation as components and shows the concept of interface and connector to ensure structural and semantic interoperability.

- The objective of the second approach is to obtain a unique model by using meta-modeling and model transformations. One of the major findings was the switch from RDP-EAD to VHDS-AMS and associated simulation [ACTI291].

Prototyping (virtual and/or real)

Virtual prototyping allows the validation of abstractions, approximations, hierarchy, and heterogeneity. We started prototyping with the connection of a simulation and a physical entity through a distributed simulation. We were able to

demonstrate that the process synchronization mechanisms of a distributed simulation can be used to ensure temporal consistency. We believe that the joint use of co-simulation and prototyping in an MDA context can lead to software/hardware architecture assessment and to incremental implementation. The feasibility of this approach was demonstrated with the description of a PN-based system which was transformed into VHDL and implemented on an FPGA microcontroller target. These activities were conducted within two application frameworks:

- Simulation as a tool for the validation of a multi-level complex system. Related work was part of a CIFRE thesis [Vincent Albert, September 30, 2009] with Airbus company, which provided an experimental field for future aircrafts with the SVA project. [ACTI612], [ACTI967], [ACTI1322], [ACTI1443], [ACTN162]
- Multi-model system (discrete-continuous) virtual prototyping. Related work was applied in an internal project of the laboratory since a hybrid PN transformation software was realized and is used today in other group or laboratory projects. [ACL71] , [ACLN5], [ACLN7]

Significant projects and collaborations

TOPCASED project

The ISI group is involved in the AESE competitiveness cluster through the TOPCASED (Toolkit in OPen-source for Critical Application & SystEms Development) project. TOPCASED is an open environment software devoted to critical embedded system design. Based on model engineering and formal methods, it must integrate different notations and different models or languages. An important part of the project is based on meta-models in order to facilitate the implementation of specialized graphic tools and model transformation tools. The ISI group contributed to the reference process definition (requirement modeling and validation with PNs) (WP1) and model transformation (sequence diagrams in PNs) (WP5) sub-tasks.

LAAS « MOCAS » internal project

The ISI group greatly contributed to the development of a *HiLeS upstream design platform* of the Mocas (Modèles et Outils de Conception Amont des Systèmes) project, proposed by the N2IS group, also conducted in collaboration with the OLC group.
This project concerns modeling and system simulation in an MDA framework. A system reference model is realized with the combination of UML models and PNs ("design process"). These models are then analysed, verified, and transformed into VHDL-AMS for simulation and virtual prototyping purposes ("System Evaluation"). The ISI group participation concerned:

- The specification of a modeling method for system requirements and needs.
- The translation of PNs into VHDL code, and EAD-PNs into VHDL-AMS code. The partial formal analysis of the discrete part, non-existent in a VHDL specification, is now possible. The continuous part is validated by simulation using a VHDL solver. [ACTI291]
- Scenario validation and verification of consistency between UML and PN uses.

ANR « ATLAS » project

ATLAS (Aides et assisTances pour la conception, la conduite et leur coupLage par les connAissanceS) is an ANR project that started in January 2007 and addresses the problems of **interaction** between the design object (the **product**) and the realization process (the **project**), and that of its optimization. The objectives of the project are summarized in the following points:

- Propose a methodology or general specification that defines the processes and the nature of inter-process exchanges, as well as their organization;
- Propose a design assistance environment and consistent interoperable tools (most of which exist but must be adapted in the project);
- Highlight cases or situations of product/project coupled design identified by industrialists who can demonstrate the relevance of the project;
- Develop a demonstrator.

Our main contributions concern the value of product design methodology, the application of System Engineering guidelines (EIA-632 standard) to the whole project, and inter-process exchange formalisation using UML notation [ACTI1488].
Our partners are: LAAS (ISI, N2IS), ENIT/LGP, EMAC/CGI, INSA/LATTIS, IMS/LAPS, Anyware Technologies, Pulsar innovation, Sigma Plus.

SVA project

The ISI group lies in the heart of the SVA (Simulation Validation Assessment) project, with the partnership of ONERA and AIRBUS-France. Its main task is identifying methods for simulation validity assessment.
The SVA project is consistent with the principle of optimization of simulation products, seen as system components. The aim is to determine the validity field of a simulation model composition. For a given experimental framework, are models of various origins, inherently heterogenous, individually validated, satisfactory when linked? Should some of

them be simplified, detailed or redefined in order to achieve the test's objectives set by the experimental framework? The expected benefits are a reduction of development cycles and simulation times, and the standardization of simulation means. A longer term goal would be the simulation's great capacity to replace certification testing and procedures, which will be less expensive if realized on "faithful" virtual systems rather than on the real airplane. Achieving this goal will also provide greater confidence towards design methodologies that inevitably use simulation. [ACTI612], [ACTI967], [ACTI1322], [ACTI1443], [ACTN162]

MUSTER tool (in collaboration with the University of Technology of Sydney)

A collaborative engineering approach for requirement elicitation was studied. Tacit knowledge and social acceptance in terms of requirements was studied. A tool (MUSTER) including a requirement elicitation method was developed. There was an extension for business assessment and the development of a collaborative structure (AIRBUS, ASTRIUM, PSA), with the University of Technology of Sydney. A joint dissertation conducted with the University of Technology of Sydney (Chad Coulin, September 25, 2007) opened new opportunities in the field.[ACL 208,ACTI 40]

ESA/PN TOOL

Based on the search for critical scenario algorithm that we developed, the ESA/PN tool allows the modeling of a hybrid system thanks to temporal or differential-predicate-transition PNs. It is interfaced to the TINA PNs analysis tool, developed at the LAAS. For a given feared state, ESA/PN provides all the critical minimal scenarios as partial order graphs. The tool is available for the scientific community on the LAAS browser (www.laas.fr/ESA) [ACTI1480, ACTI607, ACTN343].

Translation tool from Petri Nets into VHDL-AMS

This translation tool allows automatic generation of differential-predicate-transition PNs in a VHDL-AMS description. From the PN's textual description, the translation tool execution generates automatically the corresponding VHDL-AMS code. The resulting VHDL-AMS code can be directly compiled and simulated with a simulation tool [ACTI291].

HiLeS tool

HiLeS tool is a system design assistance environment using Windows ®. The system's structural component behavior is specified by PNs. Each terminal component is described in VHDL-AMS. Interfacing with TINA tool allows a formal analysis of the PN structure. With the translation of PNs into VHDL-AMS, the system's temporal analysis by simulation is possible using SystemVision ® of Mentor Graphics ®.

Distributed Computing and Asynchronism – CDA –

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Objectives and positioning

Scientific and technological environment

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 quest of 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.

Open questions

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 and many more challenges). 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. These circumstances are very propitious to research works led by scientific researchers of our team who have worked for a long time on parallel and distributed computing.

Goals and research topics

The main goals of the Distributed Computing and Asynchronism team, DCA for short, are to facilitate the use and programming of parallel and distributed computing systems at a very large scale and to propose new algorithms that will permit one to use more efficiently parallel and distributed architectures. The activity of DCA spans a domain of research that goes from the design and analysis of distributed algorithms (e.g. see [ACL6]), communication studies (see [ACTI681]) and load balancing techniques analysis (see [ACL2]), to the design of environments for distributed computing (see [ACTI80] and [INV49]). The team DCA works particularly on high performance distributed computing on general purpose architectures and dedicated architectures; e.g. DCA deals with the solution on supercomputers or peer to peer networks of large scale numerical simulation problems like boundary value problems (see [ACL308]) and difficult integer programming problems (see [ACL2]).
The team DCA works on scalability and heterogeneity (see [INV49]]; it concentrate in particular on asynchronism (e.g. see [ACL502]), a key concept to understand the very nature of distributed computing and address efficiency issues. As a matter of fact, asynchronous algorithms are well suited to all type of networks; moreover, one cannot reasonably think at synchronizing a large number of processors or processes in a massively distributed system. It turns out also that the use of asynchronous algorithms permits one to obtain better efficiency when parallel tasks are unbalanced or when convergence is monotone. Finally, asynchronous schemes of computing permit one to obtain some fault tolerance since one shows that asynchronous algorithms can converge even when some data are lost. It is important to note that asynchronism is about to become one of the main topics in Computer Science. This topic can be found in various areas of research which are the numerous facets of the same concept which consists in letting entities go at their own pace; e.g. one finds this concept in circuits, communications, processes and algorithms. For example, one speaks of asynchronous circuits when circuits have no global clock. One speaks also of asynchronous communication in message passing systems when communications aspects are not connected with synchronization aspects e.g. Remote Memory Access, RMA, or situations where there is no shake hand like protocol; one advantage being the possibility to overlap communication and computation. One also speaks about wait free processes, threads and asynchronous coprocessors.

Finally, one speaks about asynchronous iterations or asynchronous iterative algorithms when components of the iterate vector are updated without any order nor synchronization. Let us conclude by saying that these last schemes of computation are becoming more popular nowadays and that research works on communication libraries like Open MPI are pursued in University of Tennessee and other universities, in order to facilitate the use of asynchronous algorithms. Users of massively parallel architectures, like Christian Engelmann at Oak Ridge National Laboratory, recommend also the use of asynchronous algorithms for efficiency and fault tolerance purpose.
DCA deals also with self organization, another key concept in distributed computing. Far beyond self optimization, self organization is an important property in distributed decision making that permits one to obtain efficient behavior in hazardous situations or in the presence of faults and to insure everlastingness of applications.
One can find for example this 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; without such a property one can hardly think at effectiveness of entities in the system and efficiency of the whole system in general (it turns out also that any system that cannot adapt itself to an evolution context is finally condemned to dysfunction and extinction). Note finally that non synchronicity and self organization are somehow related to cooperation which is central in the domain of parallel and distributed computing, where collaborating entities share total work.

Situation of the team

The DCA team was founded ex nihilo in October 2007 according to the advices of the previous Evaluation Committee of LAAS-CNRS. Researchers in our team are affiliated to two important schools in France: first of all, a school dealing with scientific computing and in particular parallel iterative methods for PDE, 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; those collaborations are detailed in the last Section of our report. In particular, we have worked and published with almost all research teams in Computer Science, Applied Mathematics and Numerical Analysis in the world that have dealt with parallel or distributed asynchronous algorithms and we have delivered many reports on scientific papers that have been submitted to major scientific journals like Journal of Parallel and Distributed Computing, IEEE Transaction on Parallel and Distributed Systems, Parallel Computing and SIAM Journals as well as projects submitted to ANR.
It is worth noting that there is no team in LAAS-CNRS doing research work specifically on this topic and that there are relatively few teams in this country that are developing research work in this domain. 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 research works at the intersection of Computer Science and Applied Mathematics, the bulk or research works is in Computer Science, i.e. programming models, programming environments, fault tolerance and security or performance study.

Highlights and Major Achievements

Highlights

Our results during the period mainly deal with the design and analysis of parallel and distributed algorithms. Our results concern two main topics: the solution of large scale systems of equations mainly derived from boundary value problems via parallel or distributed asynchronous iterative algorithms and sequential or distributed solution of difficult integer programming problems.

"Distributed asynchronous iterative algorithms"
We have been working on this topic for a while. We have considered in particular mathematical modeling and convergence analysis (see [ACL6]), stopping criteria and study of round off errors (see [ACL56] and [ACL502]) and study of performance (see [ACL308]). We have contributed to the design and study of a new class of parallel or distributed iterative algorithms, i.e. Asynchronous Algorithms with Order Intervals, AAOI for short (see [ACL6]). The AAOI class is a general class of parallel or distributed iterative algorithms whereby several processors can perform computations, i.e. updating phases, at their own pace, without any order nor synchronization. One of the main features of this new class of algorithms is that the current value of the components of the iterate vector, i.e. a partial update which is not necessarily labeled by an iteration number can be used in the computation (see Figure 1), whereas only values labeled by an iteration number are used with the classical asynchronous iterative model. This new feature is particularly important in the case of convergence under partial ordering since it permits one to obtain better efficiency of parallel/distributed algorithms. This feature is also attractive when using two stages iterative methods or bloc iterative

methods since it is not necessary to wait for the completion of an iteration to get updates. As a consequence, the AAOI model fits new communication mechanisms like RMA and introduces more flexibility in the way data can be used in computations. Convergence results in a contraction context have been established for AAOI in [ACL6].

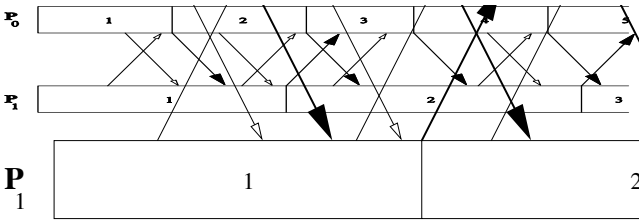

Figure 1: data exchanges in AAOI, updates exchanges (boldface) and partial updates exchanges (others)

Several theoretical stopping criteria in relationship with forward, backward or absolute errors have been proposed for perturbed asynchronous fixed point methods in the presence of round-off errors (see [ACL56] and [ACL502]). The last case is particularly interesting since all tests are made within the same macro-iteration. We have studied distributed termination detection in [ACTN5]. In particular, we have proposed a method based on activity graph and messages acknowledgement that tends to minimize the number of exchanged messages.

Issues related to the implementation of asynchronous algorithms on message passing architectures have been studied in details in [ACTI681] with emphasize on communications aspects. Efficiency of synchronous and asynchronous iterative schemes of computation has been studied for nonlinear convection diffusion problems in [ACL308]. In this last paper, computational results on IBM SP4 machines with more than one hundred processors have been analyzed in details for different communication frequencies (see Figure 2) showing the interest of asynchronous algorithms with high communication frequencies.

We have also worked on easiness of use of distributed architectures. Several generic solutions have been proposed for problems linked both to computing and networking in distributed peer to peer applications. These solutions concern initiation and termination of computation, task transparency and routing. A first series of computational results with application to shortest path problems solved via auction algorithms are presented in [ACTI80]. A self adaptive protocol for peer to peer high performance computing has also been proposed in [INV49]. The self adaptive protocol which combines micro protocols is developed in the framework of ANR Project CIP that deals with the design of a decentralized environment for distributed peer to peer computing (see also next Section).

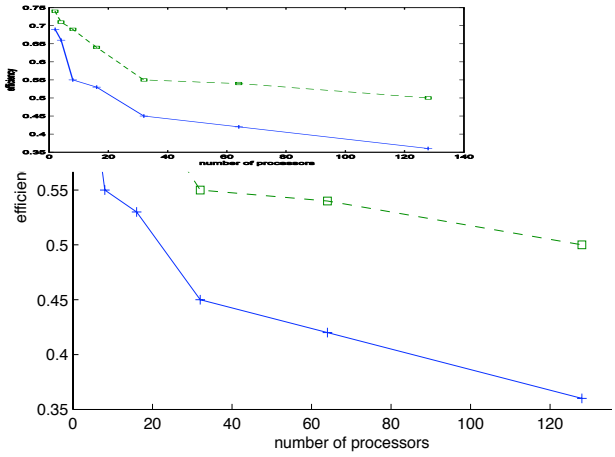

Figure 2: efficiency of parallel asynchronous algorithms (dashed) and synchronous algorithms (solid) for 3D convection-diffusion problem with 3,750,000 nodes and 256 subdomains on IBM-SP4 P690+

"Distributed methods for integer programming"

Many integer programming problems are very difficult to solve; one speaks of NP-complete problems. As a consequence, the solution of these problems is a great challenge for parallel/distributed computing. Nevertheless, most parallel/distributed solvers are derived from sequential solvers and the attractiveness of a parallel method mainly depends on the sequential method it is derived from. This is why DCA does also some research work on sequential methods for integer programming problems before deriving efficient parallel or distributed algorithms, as we shall see in the sequel.

DCA has concentrated on knapsack problems, e.g. multidimensional knapsack problems and knapsack sharing problems that arise in several practical contexts like cargo loading, capital budgeting, processor allocation and cutting stock problems. We have dealt with complexity issues. We have concentrated in particular on the origin of difficulty and the generation of difficult instances (see [ACTN241] and [TH147]).

DCA has produced a series of works on the solution of multidimensional knapsack problems. Several heuristics that outperform well known heuristics in the literature in time and quality of solution have been proposed in [ACTN178] and [EXT1]. Exact cooperatives methods that combine dynamic programming and branch and bound have been studied in [ACTI1063] and [ACTN189]. Research works have also been done on domain reduction techniques. These studies permit one to precondition problems. We have considered in particular constraint rotation methods (see [ACL551]). Let us note finally that a method based on Lagrangian relaxation has also been proposed for the solution of

combinatorial problems with equality constraints (see [ACTN170]).
A parallel dynamic programming algorithm based on lists method with pseudo polynomial complexity has been proposed for knapsack problems (see [ACL2]). Data exchange management plays a prominent part in this parallel method. Several load balancing techniques have been studied in order to obtain efficient parallel methods (see [ACL2] and [ACTI358]).

Major Achievements

We would like to put forward the set of results on asynchronous iterative algorithms quoted in the previous subsection since these results concern all the aspects related to this topic i.e. convergence analysis (see [ACL6]), stopping criteria (see [ACL56] and [ACL502]), implementation and performance analysis (see [ACL308]).
We emphasize also on the organization in LAAS-CNRS of the 16th international conference on Parallel Distributed and network-based Processing, PDP, February 13-15, 2008 (see http://www.pdp2008.org/). Dr Didier El Baz was Chair of the Organizing Committee and Chair of the Program Committee (see [DO12]). This successful conference has received 140 papers from 24 countries; this represents a 40% increase of papers as compared with previous years; 40% of papers have been selected as regular papers for publication in the Proceedings published by IEEE CPS and 120 researchers attended the conference. We have also organized a CUDA tutorial with the help of NVIDIA USA and NVIDIA France (see http://www.pdp2008.org/nvidia.html). This tutorial was also very successful with 40 participants from 8 countries.
Dr Didier El Baz was also Chair of the Program Committee of PDP Weimar, Germany, February 18-20, 2009 (see [DO20] and http://www.pdp2009.org/). Dr Didier El Baz has also organized Special Session: Integer Programming and Industrial Applications at international conference on Computers and Industrial Engineering, CIE39, Troyes, July 6-8, 2009 (see http://www.utt.fr/cie39/SSSS.htm).

Significant projects and collaborations

Significant projects

DCA is the global coordinator of project ANR CIP, ANR-07-CIS7-011, that deals with high performance peer to peer distributed computing (see http://www.laas.fr/CIS-CIP/). CIP was funded by ANR in 2007 in the framework of the so-called "Calcul Intensif et Simulation", CIS, Call for Proposal. The partners 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 [INV49]). This is an example on how we plan to address the easiness of use grand challenge. The environment is based on a self adaptive communication protocol whereby choice of communication depends on the combination of application level decisions like choice of computation scheme, e.g. synchronous versus asynchronous schemes and network level elements of context like topology, e.g. adherence to a given cluster or nearness of peers. The self adaptive protocol makes wide use of micro protocols (see Figure 3).
Market solutions that have followed the precursory SETI program are rather grid or global computing solutions (that are not totally decentralized) than actual peer to peer solutions. Peer to peer networks seem to be an attractive approach for massively distributed computing. As a consequence, there is a real economic stake at developing decentralized environments for peer to peer distributed computing applications. Peer to peer computing that permits one to use large sets of machines which are often unemployed appears also as a pragmatic "Green Computing" solution.
Aside from the development of a self adaptive communication protocol and decentralized environment for peer to peer computing, the project deals also with large scale peer to peer distributed computing simulation and performance prediction, it develops also a series of distributed solvers in financial mathematics, process engineering and logistics.

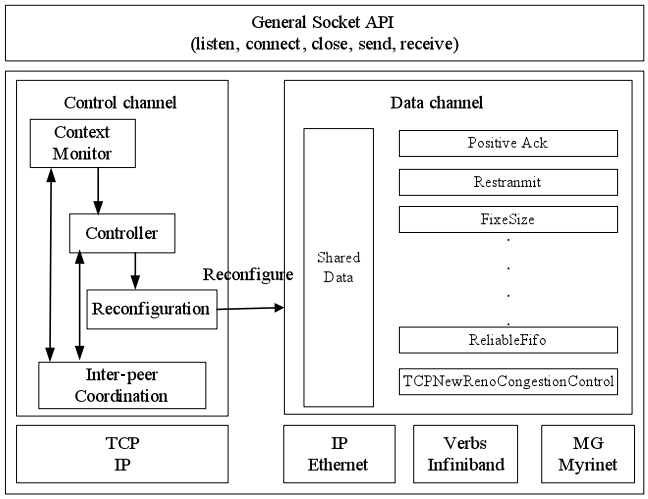

Figure 3: architecture of the self adaptive protocol

DCA is also partner of ANR ROBO 06 project Smart Surface that deals with the design of a distributed system for micro entities moving and positioning (see http://www.smartsurface.cnrs.fr/). Smart Surface aims at designing a surface based on MEMS technologies. The partners are Femto-ST (coordinator), InESS, LAAS-CNRS, LIFC and

LIMMS. The main originality of the smart surface project is to propose a completely distributed solution whereby micro parts are moved via the collaboration of a set of entities; each entity integrates sensors, a processor and actuators (see Figure 4). The Smart Surface project is an example of high performance distributed computing on a dedicated architecture. DCA designs distributed algorithms for state acquisition and pattern recognition. DCA deals also with convergence study, stopping criteria definition, algorithm validation and performance analysis.

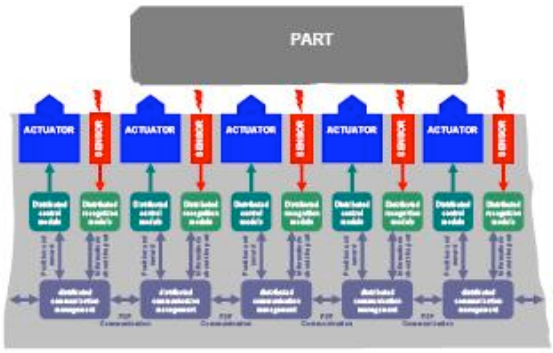

Figure 4: the distributed smart surface

Collaborations

Among the collaborations during the period, we would like to quote the long term collaboration with Jean-Claude Miellou from LCS Besançon and Pierre Spiteri from IRIT- ENSEEIHT. This collaboration on asynchronous iterations with order intervals is detailed in the Section ¨Highlights and Major Achievements¨ of this report. One can quote also the collaboration with Andreas Frommer from University of Wuppertal, Germany on convergence of asynchronous iterations. DCA is also in contact with Professor Vaidy Sunderam from Emory University, Atlanta; the topic concerns the definition of distributed computing paradigms inside Unibus. DCA works also on peer to peer distributed computing with NICTA, Eveleigh, Australia.

One can also quote the collaboration with Julien Bourgeois from LIFC Montbéliard on ANR projects Smart Surface and CIP. This collaboration was also essential to the success of the international conference Parallel Distributed and network-based Processing, PDP 2008, Toulouse (see [DO12]).

The team DCA has also cofounded working group Knapsack and Optimization, KSO, of GDR RO with Professor Mhand Hifi from University of Picardie (see http://www.laas.fr/KSO/). One can finally quote the collaboration with Gérard Plateau from Paris 13 University on constraint rotation methods (see: Highlights and Major Achievements Section).

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Annex 1
(in French)

A- Involvement of LAAS personnel in Education and University Structures

B - Courses dispensed by LAAS personnel

A- Involvement of LAAS personnel in Education and University Structures

Nom	Etablissement	Fonction
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Achaibou, A.	INP Toulouse	Membre élu du C.A. Membre élu commission de spécialistes
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Calvet, J.L.	Ecole Doctorale GEET	Membre du conseil de l'Ecole Doctorale
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Cazarre, A.	Université Paul Sabatier	Responsable du Master II Micro Nano Systèmes
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Chatila, R.	Ecole Doctorale Systèmes	Membre du conseil scientifique
Chatila, R.	INP de Toulouse	Membre du conseil scientifique
Chatila, R.	ISAE	Membre du conseil de la recherche
Chatila, R.	Université Paul Sabatier	Membre de la direction stratégique de la recherche
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Costes, A.	INPT-ENSAT	Président du conseil d'administration
Costes, A.	IUT de Figeac	Président du conseil d'administration
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Guiochet, J.	Université Paul Sabatier IUT A	Membre élu de la commission de choix, 61ème section CNU Membre élu de la commission mixte de spécialistes, 61ème section
Guiochet, J.	Université Paul Sabatier	Membre nommé du collège scientifique 61-63 ème sections
Hladik, P.E.	INSA Toulouse	Responsable de la 4ème année Informatique
Huguet, M.J.	ENI de Tarbes	Membre de la commission de spécialistes
Huguet, M.J.	INSA Toulouse	Membre du conseil d'administration Membre de la commission de spécialistes en 27ème section Membre du comité de sélection poste MCF Informatique Membre du conseil de département STPI INSA Responsable du conseil d'orientation de la filière informatique du GEI - Directrice des études GEI
Jauberthie, C.	Université Paul Sabatier	Responsable de la Licence 3 dans le département d'ingénierie du diagnostic, de l'instrumentation et de la mesure (UFR-PCA)
Josefowiez, N.	INSA Toulouse	Responsable de la 3ème année MIC
Kaâniche, M.	Université Paul Sabatier	Membre de la commission de spécialistes 61ème section

Labit, Y.	Université Paul Sabatier, UFR-PCA	Membre élu de la commission de spécialistes 61ème section Membre de la commission communication
Landa, G.	Conseil National des Universités (CNU)	Membre du CNU 28ème section (membre du bureau)
Landa, G.	Université Paul Sabatier	Responsable d'un Master Pro Membre du collège scientifique « Physique »
Launay, J.	Université Paul Sabatier, IUT	Membre permanent de la commission GHS Responsable du Pôle EEA au département Mesures Physiques Elu au conseil de département Responsable pédagogique de la 2ème année IUT
Le Botlan, D.	INSA Toulouse	Membre élu du conseil de département du DGEI Responsable de l'enseignement algorithmique en 1ère année
Lerasle, F.	Université Paul Sabatier	Responsable de L3 IUP Systèmes Intelligents Membre du département EEA
Llopis, O.	INSA Toulouse	Membre du collège scientifique
Lopez, P.	Ecole Doctorale EDSYS	Membre du Comité Directeur
Lopez, P.	Université Paul Sabatier, UFR-PCA	Membre élu au Conseil Scientifique de l'UFR-PCA Membre élu de la CSE 61ème section
Lopez, P.	INSA Toulouse	Membre nommé de la CSE 27ème section et de la CSE mixte 61-63/27èmes sections
Lopez, P.	IUT de Bordeaux	Membre comité de sélection poste MCF
Lozes, F.	Ministère Délégué à l'Enseignement Supérieur et à la Recherche	Chargée de Mission au département STIC de la Mission Scientifique Technique et Pédagogique du Ministère Délégué à l'Enseignement Supérieur et à la Recherche
Lozes, F.	Société Française d'Optique	Secrétariat de la commission Enseignement
Lozes, F.	Université Paul Sabatier	Membre du collège scientifique EEA
Menini , P.	Université Paul Sabatier	Responsable de la Licence professionnelle CPSE Membre du GAP 60e/61e/62e/63e section Membre du collège scientifique 61e/63e section
Mercé, C.	ENI de Tarbes	Membre suppléant au conseil scientifique
Mercé, C.	INSA Toulouse	Directrice du département Génie Electrique et Informatique Membre élu au CA de l'INSA. Présidente du CA restreint (jusqu'en juillet 08). Vice-Présidente (depuis juillet 08) Membre du CTP
Monteil, T.	Centre Interuniversitaire de Calcul de Toulouse	Membre du conseil d'administration
Monteil, T.	INSA Toulouse	Responsable 5ème année informatique
Monteil, T.	Presses Universitaires du Mirail	Co-directeur de la collection d'ouvrage « pour l'ingénieur »
Morancho, F.	Université Paul Sabatier	Responsable du Master 2 Pro ISME Vice-président du comité de sélection 63ème section
Nketsa, A.	Université Paul Sabatier	Chef de département de GEII (jusqu'à 2006) Chef de département adjoint GEII Membre élu au collège scientifique EEA
Nicomette, V.	INSA Toulouse	Responsable de la 5ème année Réseaux Télécom Représentation du département info au CARI (conseil d'administration du CRI)-Membre du comité d'orientation Réseaux Télécom du département info

Paludetto, M.	Université Paul Sabatier	Directeur de l'IUP ISME (jusqu'au 30/08/08) Directeur-adjoint de l'IUP ISME Responsable de l'accord multilatéral de coopération France-Italie pour l'attribution de doubles diplômes (secteur des STIC&A) Membre de la commission de spécialistes 61ème section
Parra, T.	Université Paul Sabatier	Vice-Président de l'Université, délégué aux relations européennes Membre du conseil scientifique Membre du collège scientifique (sections 61-63) Membre du bureau de l'ED AA
Pascal, J.C.	Université Paul Sabatier	Directeur du département EEA Responsable du Master Professionnel Productique Membre de la commission Sciences, Technologies, Santé de la Direction Stratégique de l'Enseignement Porteur du projet de Master EEA pour le contrat quadriennal 2011-2014 Membre des comités de sélection pour les postes 61ème section
Peaucelle, D.	INSA Toulouse	Membre de la CSE 61/63
Pradin-Chezalviel, B.	ENFA Ecole Nationale de Formation Agronomique)	Membre nommé du CA
Pradin-Chezalviel, B.	IUFM de Toulouse	Membre nommé du CA
Pradin-Chezalviel, B .	Ministère de l'Enseignement Supérieur	Membre de la commission nationale d'expertise des Licences Professionnelles Membre de la commission consultative nationale des IUT
Pradin-Chezalviel, B.	PRES Université de Toulouse	Délégation au PRES Membre élu du CA du PRES
Pradin-Chezalviel, B.	Université Paul Sabatier	Vice-présidente (CEVU) Membre élu du CA et du Bureau Chargée de Mission (Licences Professionnelles) de l'IUT A
Prieur, C.	Université Joseph Fourier, Grenoble	Membre du comité de sélection d'une chaire
Queinnec, I.	Université Paul Sabatier	Membre du conseil scientifique Membre de la commission des HDR Membre invitée du conseil scientifique de l'UFR-PCA Membre de la CSE 61
Rivière, N.	Université Paul Sabatier, UFR-PCA	Membre élu au conseil de département EEA Membre du conseil pédagogique
Roux, G.	Université Paul Sabatier	Directeur des études au département GEII de l'IUT
Roy, M.	Université de Rennes	Membre du comité de sélection MC poste système
Sanchez, JL.	INP - Toulouse	Membre de la commission de spécialistes 61-63
Sanchez, JL.	Université Paul Sabatier	Membre de la commission de spécialistes 61-63
Sautereau, J.F.	Ecole des Mines d'Albi-Carmaux	Membre du CA
Sautereau, J.F.	Université Paul Sabatier	Président (2002-2008)
Senac, P.	Ecole Doctorale MITT	Membre du bureau Informatique/Télécom
Senac, P.	ISAE	Responsable ISAE pour le master recherche informatique et Telecom - Chef du DMIA
Siméon, T.	INSA-DGEI	Membre Commission de Recrutement

Subias, A.	Conseil National des Universités (CNU)	Membre élu du CNU 61ème section
Subias, A.	INSA Toulouse	Membre élu du collège des maîtres de conférence de la commission de spécialistes des 61-63ème sections EEA-Génie Informatique Membre élu du conseil de département du département de Génie Electrique et Informatique
Taix, M.	GAP Ingénierie	Président
Taix, M.	Université Paul Sabatier	Directeur du parcours IUP Systèmes Intelligents Représentant des IUPs au GIPI Membre élu du collège scientifique EEA
Tartarin, J.G	Université Paul Sabatier	Responsable du master 2 MEMO Responsable du master 1 électronique
Tartarin, J.G.	Université Paul Sabatier, UFR-PCA	Membre du conseil pédagogique
Tazi, S.	Université Paul Sabatier	Membre élu de la commission de spécialistes 27 Membre élu du conseil d'UFR Informatique
Tounsi, P.	INSA Toulouse	Membre élu du conseil de département Génie Electrique et Informatique Membre nommé du comité de sélection du DGEI
Tournier, E.	Université Paul Sabatier, UFR-PCA	Membre du conseil d'administration
Tournier, E.	Université Paul Sabatier	Membre du collège scientifique (sections 61-63)
Travé-Massuyès, L.	Conseil National des Universités (CNU)	Membre nommé du CNU pour la section 61
Travé-Massuyès, L.	Université Paul Sabatier	Membre du collège scientifique EEA
Travé-Massuyès, L.	INSA Toulouse	Membre de la commission de spécialistes 61-63 EEA Génie Informatique
Vernadat, F.	INP – ENSEEIHT	Membre nommé de la commission de spécialistes 27
Vernadat, F.	INSA Toulouse	Membre élu 27 de la commission de recrutement Président du comité de sélection 27/61 poste MCF
Vernadat, F.	Université Toulouse 1	Membre nommé de la commission de spécialistes 27
Vieu, C.	INSA Toulouse	Membre du conseil de département Génie Physique Membre du comité de sélection de la 28ème section
Waeselynck, H.	INSA Toulouse	Membre de la commission de spécialistes 27ème section
Waeselynck, H.	Université Paul Sabatier	Membre du collège scientifique EEA

B - Courses dispensed by LAAS personnel

Nom	Etablissement	Niveau
Alami, R.	Supelec Metz	Robotique 3ème année
Alami, R.	Université de Zaragoza	Cours Robotique autonome
Alami, R.	Université Paul Sabatier	Cours Ecole doctorale Edsys
Almuneau, G.	Université Montpellier II	Master Phymatec
Arnoult, A.	INSA Toulouse	1ère année Ecole d'Ingénieurs
Arzelier, D.	ISAE ENSICA	L3 et M2
Artigues, C.	INSA Toulouse	Doctorants
Artigues, C.	Université Paul Sabatier	M2R
Bary, L.	Université Paul Sabatier, IUT	L2
Baudoin, L.	INSA Toulouse	L2
Baudoin, L.	ISAE, Supaero	L3
Baudoin, L.	ISAE, ENSICA	L3
Brun, O.	INSA Toulouse	5ème année
Brun, O.	Université Paul Sabatier	Master 2 Recherche
Camps, F.	ENSICA	M2
Camps, F.	INSA Toulouse	L3 et M1
Carcenac, F.	Centre Brésilien de Recherche en Physique	Doctorants et chercheurs
Carcenac, F.	Ecole d'été européenne	Doctorants et chercheurs
Carcenac, F.	Ecole d'été sur les nanotechnologies	Doctorants et chercheurs
Chatila, R.	Université Paris 6	Master 2 Robotique
Chatila, R.	Université Paris 8	Master 1 et Master 2 Robotique
Conedera, V.	AIME	Industriels
Conedera, V.	IMS	Master 2
Conedera, V.	ENSIACET	Master 2
Conedera, V.	INP (ENSEEIHT)	3ème année
Cortes, J.	Université Paul Sabatier	Master Edsys
Cortes, J.	Université de Valence (Espagne)	Master
Cortes, J.	Université Paul Sabatier	Master Pro IM2P2
Coustou, A.	INSA Toulouse	L3
Cristiano, F.	Université Paul Sabatier	Mastère ISME
De Bonneval, A.	Université Paul Sabatier	M2, M1, L3 IUP et L1 CIMP

Deswarte, Y.	INSA Toulouse, Université Cheikh Anta Diop de Dakar, EMIAE (Ecole Marocaine d'Informatique, Automatique, Electronique)	Divers cours en Master et en dernière année d'école d'ingénieurs
Deswarte, Y.	Centre Universitaire de Formation et recherche « Jean-François Champollion »	Formation ISIS
Devy, M.	Université Paul Sabatier	M2P IRR
Drira, K.	INSA	5ème année RT et GI
Drira, K.	ISAE	3ème année
Dubreuil, P.	AIME	3ème année Ecole d'Ingénieur et Formation permanente industriel
Fabre, N.	AIME	Bac+2 à Bac+5
Fabre, N.	ENSCT	Master
Fabre, N.	IMS	Master
Filipowicz, A.	CIES	Enseignement niveau Doctorat
Filipowicz, A.	IEP Toulouse	Enseignement niveau Master
Filipowicz, A.	ISAE	DESII du cycle ENSICA
Fontaine, C.	INSA Toulouse	5ème année
Garcia, J.M.	Université Paul Sabatier	Master 2 Recherche
Granier, H.	Lycée professionnel Bourdeille	BTS
Grenier, K.	INSA Toulouse	2nd cycle
Grenier, K.	Université Paul Sabatier, IUT	1er cycle
Gué, A.M.	INP (ENSEEIHT)	5ème année
Henrion, D.	Graduate Paris School on Control (HYCON)	PhD
Henrion, D.	INSA-UPS-INP-ISAE Ecole Doctorale	PhD
Henrion, D.	Université de Valence et Université de Valladolid (Belgique)	PhD
Henrion, D.	Université de Torun (Pologne)	PhD
Henrion, D.	Université de Prague (République Tchèque)	PhD
Henrion, D.	Université de Calabre (Belgique)	PhD
Henrion, D.	Université de Dortmund (Belgique)	PhD
Henrion, D.	Université de Leuven (Belgique)	PhD
Herrb, M.	INP (ENSEEIHT)	M1

Imbernon, E.	AIME	3ème année Ecole d'Ingénieurs Formation Continue
Kanoun, K.	ENAC	3ème année
Kanoun, K.	ENSEIRB	2ème année
Kanoun, K.	IAS	Formation continue
Kanoun, K.	ISAE – Sup'Aero	3ème année
Killijian, M.O.	EMN	M1
Killijian, M.O.	ENSEEIHT	L2 et M1
Killijian, M.O.	ENSEIRB	L2 et M1
Killijian, M.O.	ISAE/ENSAE	M1
Lacroix, S.	ISAE	3ème année filière image de SupAero
Laprie, J.C.	ENSEIRB	2ème année
Laprie, J.C.	ICSI	Master
Laprie, J.C.	ISAE-ENSICA	Master
Laprie, J.C.	ISAE-ENSICA et ENAC	Master conjoint
Laprie, J.C.	ISAE-Sup'Aero	3ème année
Lasserre, J.B.	ETH Zurich et Ascona	Ecole d'été (PhD)
Lasserre, J.B.	Université Pierre et Marie Curie	M2
Lasserre, J.B.	Zinal Suisse	PhD
Laumond, J.P.	Ecole Nationale Supérieure des Techniques Avancées (ENSTA)	M2
Laumond, J.P.	Ecole Nationale Supérieure-Ulm	M2
Lemaire, C.	Université Paul Sabatier, IUT	L2
Llopis, O.	Université Paul Sabatier, IUT	Master 2 MEMO et ICEM
Lopez, P.	ENSIACET	3ème année
Lopez, P.	Faculté des Sciences de Tunis	M2R
Lopez, P.	INSA Toulouse	5ème année + Doctorants
Lopez, P.	Université Paul Sabatier	M2R
Lozes, F.	Université Paul Sabatier	Master Recherche CCMM
Marty, A.	Université Paul Sabatier	Master 2 Recherche
Mathieu, F.	INSA Toulouse	M1
Monin , A.	Université Paul Sabatier	Master 2 Recherche
Nicu, L.	INSA Toulouse	5ème année Biologie, Physique
Nicu, L.	Université Paul Sabatier	Master Pro ISME
Owezarski, P.	INP - ENSEEIHT	Master 3ème année RT

Owezarski, P.	INSA Toulouse	Master 5ème année RT
Peaucelle, D.	ENAC	M2
Peaucelle, D.	ISAE, ENSICA	L3 et M1
Pons, J.M.	ENSICA	1ère année Cycle ingénieur
Pons, J.M.	INSA Toulouse	DGEII 4ème année
Pons, J.M.	Université Paul Sabatier, IUT	DGEII, 2ème année
Powell, D.	ISAE	5ème année Ingénieur/ Master recherche 2ème année
Powell, D.	Université Paul Sabatier	Master Recherche 2ème année
Prabhu, B./Ayesta, U.	INSA Toulouse	5ème année
Prieur, C.	CNAM	L2
Prieur, C.	INSA-UPS-INP-ISAE Ecole Doctorale	PhD
Prieur, C.	Graduate Paris School on Control (HYCON)	PhD
Queinnec, I.	ISAE-ENSICA	L3 et M1
Queinnec, I.	Université Rovira i Virgili (Tarragone, Espagne)	M2
Rousset, B.	AIME	3ème année Ecole d'Ingénieur et Formation permanente industriel
Rousset, B.	Ecole d'été du programme européen GASMEMS	3ème année Ecole d'Ingénieur
Sanchez, J.L.	INP (ENSEEIHT)	5ème année
Sanchez, J.L.	Université Paul Sabatier	Master 2
Silvain, I.	Université Paul Sabatier, IUT	L1
Silvain, I.	Université Paul Sabatier	L3
Siméon, T.	Université Paul Sabatier	Cours M2R SAID
Séguier, L.	Université Paul Sabatier	L3
Tarbouriech, S.	INSA-UPS-INP-ISAE Ecole Doctorale	PhD
Tarbouriech, S.	UNICAMP (Brésil)	M2 et PhD
Tarbouriech, S.	Université de Seville (Belgique)	M2
Tarbouriech, S.	Université Rovira i Virgili (Tarragone, Belgique)	M2
Tarbouriech, S.	Université de Louvain-La-Neuve (Belgique)	PhD
Temple-Boyer, P.	ENSIACET	Option 3ème année MAFO
Temple-Boyer, P.	Université Paul Sabatier	Mastères AISEM et C2M2
Vandeportaele, B.	ENSEEIHT	TP ingénieur
Vandeportaele, B.	ISAE	Cours Ingénieur
Zanon, C.	INSA Toulouse	L3 et M1

ANNEX 2

Training actions 2005-2009
(in French)

I. Contexte :

Le LAAS est inscrits depuis de nombreuses années dans une démarche de Formation. Le 1er plan de Formation du LAAS a été élaboré en 1994

Le dernier Plan de Formation correspond au quadriennal 2006/2009..

Le texte qui suit a pour objectif de brosser un tableau de la réalisation de ce Plan de Formation, en termes de formation suivies par les personnels durant cette période et de formations dispensées par les personnels de l'unité.

II. Bilan détaillé des formations suivies par des personnels du laboratoire de 2005 à 2009

En préambule, nous tenons à préciser que de nombreux besoins issus du Plan de Formation ont été satisfaits avec l'aide précieuse du bureau de la Formation de la Délégation régionale Midi-Pyrénées. Cette aide s'est manifestée par le financement de formations extérieures, ainsi que l'organisation et la mise en place de stages directement par le bureau de la Formation de la Délégation Régionale (Formation sécurité Laser, compatibilité électromagnétique des installations, formation habilitation électrique pour l'ensemble des personnels du laboratoire concernés); enfin par le financement de formations spécifiques répondant à des besoins individuels ou collectifs tels que la formation sécurité gaz, Microscopie à l'échelle atomique…. Il est à noter que le laboratoire fait également des efforts importants pour financer ou participer au financement de formations, soit par la prise en charge des frais de mission des stagiaires, soit par le co-financement, à titre d'exemple une formation au logiciel de conception et de calcul optique ZEMAX a été financé à parts égales par la délégation Midi-Pyrénées le CESR et le LAAS. Le laboratoire a également mis l'accent durant cette période sur les formations dans de domaine de l'Hygiène et la sécurité, en formant notamment 20 Sauveteur Secouristes du Travail, le laboratoire étant sous dotés, et en s'engageant à financer les formations recyclages de ces personnes.

Quelques chiffres illustrant le bilan de la formation au LAAS durant ce quadriennal, le nombre de formations suivies annuellement est de 150, 65% de ces formations ont été suivis par des ITA et ITAOS, 24 % par des doctorants et des post-doctorants, 11 % par des chercheurs et des enseignants chercheurs.

Tableau synthétique des formations suivies par les personnels de l'unité du 1/9/05 au 30/6/09

Type	Nombre total	Libellé	Nombre de personnes formées	Organisateur
ACMO	1	Formation initiale ACMO	1	CNRS Délégation Midi Pyrénées
Bureautique	10			
		Word	2	CNRS Délégation Midi Pyrénées
		Excel calcul avancé	2	CNRS Délégation Midi Pyrénées
		Powerpoint	2	CNRS Délégation Midi Pyrénées
		PAO infographie	4	
Ecoles	6			
		"Contraintes Internes : de leurs origines à leur utilisation dans les matériaux à propriétés électroniques	1	CNRS National
		Solitons dansles cavités optiques	2	CNRS National
		ECOFAC 06	1	CNRS National
		MOVEP 2006	2	CNRS National
Générales	91			
		1ère rencontre régionale des correspondants information	1	CNRS National
		Accueil Chercheurs IT recrutés Département ST2I	5	CNRS National
		Accueil régional des nouveaux entrants CNRS	5	CNRS Délégation Midi Pyrénées
		Action de sensibilisation pour l'emploi des personnes handicapées	3	CNRS Délégation Midi Pyrénées
		Améliorer la qualité en recherche, la tracabilité et la capitalisation des connaissances dans les laboratoires de ST2I	2	CNRS National
		Améliorer sa mémoire	3	CNRS Délégation Midi Pyrénées
		Cadre juridique du métier d'ASR	1	CNRS National
		Comment accéder aux financements européens	2	CNRS National
		Conduite de projet	6	CNRS Délégation Midi Pyrénées
		Coopération territoriale européenne	1	CNRS National
		Correspondant technique du bâtiment	1	CNRS National

Ethique et déontologie: pour mieux travailler ensemble	3	CNRS Délégation Midi Pyrénées
Formation des Présidents et Membres de jury de Concours Externes2008	4	CNRS National
Formation documentaliste	2	CNRS National
Itinéraires : repérer et construire son parcours de chercheur	2	CNRS National
Journée thématique / Co-utilisateurs sur les initiatives Technologiques Conjointes	1	CNRS National
La propriété intellectuelle au service de la recherche	1	INPI
LABINTEL Débutants 2005	2	CNRS Délégation Midi Pyrénées
Lecture rapide	1	CNRS Délégation Midi Pyrénées
Management de Projet	1	CNRS National
Management des projets européens 7ème PCRD	1	Interface europe
Obligation juridique et responsabilité en matière de santé et de sécurité au travail	1	INPT
optimisez votre prise de note et la rédaction des comptes-rendus	3	CNRS Délégation Midi Pyrénées
Organisation de vos séminaires étapes par étapes	2	Florence Molière Consulting
Orthographe, tendre vers le zéro faute	7	CNRS Délégation Midi Pyrénées
Outils de veille : surveiller l'information sur internet	2	ADBS
Pérenniser le document numérique	1	ADBS
Préparation aux épreuves "prime de fonctions informatiques"	2	CNRS Délégation Midi Pyrénées
Préparation à la retraite	6	CNRS Délégation Midi Pyrénées
Préparation aux concours internes	7	CNRS Délégation Midi Pyrénées
Projets du 7ème PCDR-Montage d'une proposition compétitive	3	CNRS Délégation Midi Pyrénées
Projets du 7ème PCDR-Suivi administratif et financier	4	CNRS Délégation Midi Pyrénées

		Se mettre en conformité avec la réglementation CNIL	2	CNRS Délégation Midi Pyrénées
Informatique	43			
		Administration ORACLE	1	Iform
		AJAX	1	SQLI
		Analyse et conception avec UML	1	Altech
		Autocad avancé 3d	1	LASCOM
		Catia V5: les fondamentaux de base	1	Daussault Systèmes
		Conception numérique et VHDL	3	ISAE
		Formation au logiciel PMB	6	PMB service
		Imagerie Numerique en Biologie	1	CNRS Délégation Midi Pyrénées
		Initiation à Vista	1	CICT
		JAVA : concepts avancés du langage	1	SQLI
		Journées Réseau	4	CNRS National
		Langage C++	8	CNRS Délégation Midi Pyrénées
		Les bases du langage PERL	1	SQLI
		Linux administration de serveurs	1	CICT
		Maintenance et dépannage vista	1	CICT
		Matlab à la carte	2	CNRS Délégation Midi Pyrénées
		Mise en œuvre des microcontrôleurs Microchip PIC18	1	CNRS Délégation Midi Pyrénées
		Nouveaux outils mathématiques pour l'analyse d'images et la vision par ordinateur	1	CNRS Délégation Midi Pyrénées
		Traitement de l'image sous logiciel Image	1	INSERM
		Vware Infrastructure : Install and Configure	1	CICT
		WEB 2009	5	CNRS Délégation Midi Pyrénées
Langues	91			
		Anglais	59	CNRS Délégation Midi Pyrénées
		Anglais	5	Pôle Universitaire européen
		Espagnol	1	CNRS Délégation Midi Pyrénées
		Espagnol	1	Réseau Universitaire Midi-Pyrénées
		Français Langue Etrangère	22	CNRS Délégation Midi Pyrénées

		Japonais	3	Réseau Universitaire Midi-Pyrénées
Réseaux	40			
		Réseau correspondants bâtiments	1	CNRS Délégation Midi Pyrénées
		Réseau documentaliste	7	INIST
		Réseau des électroniciens	29	CNRS Délégation Midi Pyrénées
		Réseau des mécaniciens	4	CNRS Délégation Midi Pyrénées
Sauveteurs Secouristes du travail (Initial ou recyclage)	44			CNRS Délégation Midi Pyrénées / LAAS
Technique	51			
		Analyse de la réplication et de l'instabilité génétique	2	INSERM
		Compatibilité électromagnétique des installations	15	AEMC
		Conception des équipements électroniques	2	AEMC
		Fibres Optiques	1	IRCOM Limoge
		Formation de base Autocad	4	LASCOM
		Formation PIC	2	Microchip
		Initiation à la chimie	1	CNRS Délégation Midi Pyrénées
		Microscopie à force atomique	5	INSA Toulouse
		Physique des moteurs moléculaires - Mesures à l'échelle de la molécule unique	1	INSERM
		PIC 24 et dsPIC Architecture	5	CNRS Délégation Midi Pyrénées
		PSOC	5	LGC Toulouse
		Ressources de Microscopie	1	INRA
		Synthèse et traitement de Nano particules par Plasmas basse pression	2	CNRS National
Sécurité	39			
		Habilitation électrique (Niveau 0 à 2)	23	ASFO
		Sécurité Gaz	8	Gaz Technologie
		Formation initiale personne compétente en radioprotection sources scellées	1	Norisko