INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Icare

Instrumentation, Commande et Architecture des Robots Évolués

Sophia Antipolis

THEME NUM

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1. Team

Head of project-team
Claude Samson [DR]

Vice-head of project-team
Patrick Rives [DR (50% Action VISA)]

Administrative assistant
Patricia Maleyran [TR (part-time), from Jan. 2005 to May 2005]
Christel Kozinski [TR (part-time), from June 2005 to Dec 2005]

INRIA staff
Pascal Morin [CR]
Ezio Malis [CR]

Ph. D. students
Nicolas Simond [ATER]
Matthieu Fruchard [INRIA grant, until June 2005]
Selim Benhimane [INRIA grant]
Mauro Maya Mendez [SFERE-CONACYT grant]
Christopher Mei [DGA grant]
Vincent Brandou [Ifremer/PACA grant]
Geraldo Silveira [Brasilian CAPES grant]

Post-doctoral fellow
Doojin Choi [Corean grant, until Sept. 2005]
Andrew Comport [INRIA grant, from Nov. 2005 to Nov. 2006]

Associated Engineer
Alessandro Corrêa-Victorino [contract ECA/MiniRoc]

Professor Visitor
Manuel Vargas [spanish grant, Nov 2004 - Feb 2005]

2. Overall Objectives

2.1. Overall Objectives

The project-team activities are centered on the modeling and control of robotic systems (manipulator arms, mobile robots, aerial vehicles, ships and submarines,...) destined to accomplish with some degree of autonomy complex tasks strongly interacting with the system's environment. The important structural nonlinearities of many of these systems call for the development of new control techniques, whereas autonomy relies upon the use of sensory information for environment perception and modeling, motion planning, and the definition of navigation strategies. Solutions to the multiple facets of overall control problem have to be combined with the ever present preoccupation of robustness and real-time implementability. Accordingly, our approach to the robot control problem is not limited to the sole preoccupation of designing control algorithms. It also involves complementary aspects such as the modeling of interactions with the environment and the development of sensory capacities needed for the completion of the task objectives. In this respect, validation and testing on physical systems is essential, not only as a means to bring together all aspects of the research done in Icare –and thus maintain the coherence and unity of the project-team–, but also to understanding the core of the problems on which research efforts should focus in priority. To this aim, a significant part of our resources is devoted to the development of experimentation facilities that are proper to the project, notably an indoor mobile robot prototype, called ANIS, equipped with a manipulator arm, an ultrasonic sensor-belt, a rotating laser range finder, and a real-time image acquisition and processing system. These facilities constitute an experimental workbench for the research done in the project. Another platform is an electrically powered car-like vehicle called CyCab that the VISA team manages at Sophia-Antipolis for transversal research purposes. Replicas of the CyCab are found at other INRIA sites. They form a small fleet of wheeled vehicles for the research community on the general theme of intelligent and autonomous transportation in urban environment. In parallel, we try to develop other means of experimentation in partnership research programs, for example with the IFREMER concerning underwater robotics, and with the CenPRA of Campinas (Brazil) and I.S.T. of Lisboa (Portugal) on the control of unmanned aerial vehicles (drones and blimps).

3. Scientific Foundations

3.1. Introduction

Building *intelligent autonomous* robots will remain a formidable challenge for decades to come. It is now widely acknowledged in the Robotics community that progress in this direction goes with the study of a number of sub-problems a large set of which can be regrouped under the headings of *robot modeling and control*, *perception* and *robot navigation*.

3.2. Robot modeling and control

Keywords: *holonomic system*, *legged robot*, *manipulator arm*, *mobile robot*, *nonholonomic system*.

Participants: Claude Samson, Pascal Morin, Matthieu Fruchard, Mauro Maya Mendez.

Robotic mechanisms are usually designed according to the applications and tasks to which they are destined. A coarse classification distinguishes three important categories, namely

- i) *manipulator arms,* frequently present in manufacturing environments dealing with parts assembly and handling,
- ii) *wheeled mobile robots,* whose mobility allows to address more diversified applications (manufacturing robotics, but also robotics for servicing and transportation), and
- iii) *legged robots*, whose complexity and more recent study contribute to explain why they are still largely confined to laboratory experimentation.

This common classification does not entirely suffice to account for the large variety of robotic mechanisms. One should, for instance, add all hybrid mechanisms resulting from the association of a manipulator arm mounted on a mobile platform, as well as robotized marine vehicles (ships and submarines) and aerials (drones, blimps).

Each category infers specific motion characteristics and control problems. The mathematical formalisms (of Newton, Euler-Lagrange,...), universally utilized to devise —generically *nonlinear*— dynamic body model equations for these systems, are classical and reasonably well mastered by now. At this level, the differences between manipulator arms and wheeled vehicles mostly arise from the existence of two types of *kinematic linkages*. In a general manner, these linkages (or constraints) are exclusively *holonomic*, i.e. completely integrable, in the case of manipulator arms, while the wheel-to-ground contact linkage which is common to all wheeled mobile robots is *nonholonomic*, i.e. not completely integrable. For this reason, it is often said that manipulators are holonomic mechanical systems, and that wheeled mobile robots are nonholonomic. A directly related structural property of a holonomic mechanism is the equality of the dimension of the *configuration space* and the number of *degrees of freedom*, i.e. the dimension of possible instantaneous velocities, of the system. The fact that the dimension of the configuration space of a nonholonomic system is, by contrast, strictly larger than the number of degrees of freedom is the core of the greater difficulty encountered to control this type of system.

The application of classical theorems in differential geometry, in the framework of Control Theory, nevertheless allows us to infer an important functional property shared by these two types of systems when they are *completely actuated*, i.e. when they have one actuator per degree of freedom. This is the property of being (kinematically) *locally controllable* at every point in the state space. It essentially means that, given an arbitrary small period of time, the set of points which can be reached by applying bounded control inputs contains a whole neighborhood of the initial point. This is a *strong* controllability property. It implies in particular that any point in the state space can be reached within a given amount of time, provided that the control inputs are allowed to be large enough. In other words, the robotic mechanism can reach any point in its configuration space, and it can do it as fast as required provided that the actuators are powerful enough.

The case of *underactuated* systems, which may correspond to a ship which does not need lateral propellers to fulfill its nominal missions, or a manipulator with an actuator no longer responding, is much more complex and has, until now, resisted attempts (not yet many, one must add) of classification based on the various notions of controllability. Let us just mention that some of these systems remain controllable in the sense evoked previously, while others lose this property but are still controllable in a weaker sense, and others just become uncontrollable for all practical purposes.

The controllability of a completely actuated robotic system does not yet imply that the design of adequate control laws is simple. In the most favorable case of holonomic manipulators, the system's equations are *static state feedback linearizable* so that it can be said that these systems are “weakly” nonlinear. The transposition of classical control techniques for linear systems then constitutes a viable solution, often used in practice. By contrast, the linearized model of a nonholonomic mobile robot, determined at an arbitrary fixed configuration, is not controllable. The exact input-to-state linearization of the equations of such a robot via a dynamic feedback transformation, when it is possible, always presents singularities at equilibrium points. The perhaps most striking point, as for its theoretical and practical implications, is that there does not exist pure-state continuous feedback controls capable of asymptotically stabilizing a desired fixed configuration. This underlies the fundamentally nonlinear character of this type of system and the necessity to work with control techniques that depart sharply from the classical methods used for linear or linearizable systems.

The case of legged robots, and of articulated locomotion in general, is yet very different in that most of these systems do not fit in the holonomic/nonholonomic classification mentioned previously. Setting them in equations requires decomposing their motion into several phases (according to the number of legs in contact with the ground). Ballistic phases (when no leg touches the ground) often involve non-holonomic constraints arising from the conservation of the kinetic momentum, and also the modeling of impact phenomena occurring at time instants when a leg hits the ground. The analysis of the way these systems work is astonishingly complex, even for the simplest ones (like the walking –biped– compass and the hopping –single legged– monopod). It becomes even more involved when further exploring the correspondence between some nominal modes of motion of these systems and various *gaits* of biological systems (such as walking, running, trotting, galloping,...) with a comparable structure. It is now commonly accepted, although imperfectly understood, that the existence of such pseudo-periodic gaits, and the mechanisms of transition between them, are closely related to energy consumption aspects. Following this point of view, the control strategy relies on the “identification” of the trajectories for which energy consumption is minimal, prior to stabilizing them.

One of the research objectives of the project ICARE is to make the control solutions for these different robotic systems progress. This research has in the past produced collaborations with other Inria projects, such as MIAOU at Sophia-Antipolis, and the former project BIP in Grenoble.

Since robotic, or “robotizable”, mechanisms are structurally nonlinear systems which, in practice, need to be controlled in an efficient and *robust* manner, the project ICARE has natural interest and activities in the domain of Automatic Control related to the theory of control of nonlinear systems. Concerning fundamental and methodological developments conducted around the world in this domain, the study of mechanical systems and their automatization –which is the core of Robotics– has played, and continues to play, a privileged role [51]. This has a historical foundation, since one can argue that Automatic Control, as an engineering science, started with the regulation of mechanical systems. Let us cite, for instance, the centrifugal regulator of Watt in the 18th century, the automated ship pilots of Minorsky in 1922, and the problems of guidance and stabilization of aerial and space devices during the Second World War. More recently, the manipulator arms have been used as a model to illustrate the interest of feedback control linearization. The studies of robustness with respect to modeling errors (arising from uncertainties about the mechanical parameters, the exteroceptive sensors' parameters, or the environment observed via the sensors) have allowed to refine the stability analyses based on Lyapunov functions and to illustrate the interest of approaches which exploit the structural passivity properties associated with hamiltonian systems. Even more recently, the study of nonholonomic mobile robots has been the starting point for the development of new approaches, such as the characterization of differential *flatness* [50], used to solve trajectory planning problems, and *time-varying feedback control* techniques [43], used to solve the problem of asymptotic stabilization of a fixed point.

In this context, the research done in the ICARE project mainly focuses on feedback control stabilization issues. In the case of the manipulator arms, it has produced the so-called *task function* approach [19] which is a general framework for addressing sensor-based control problems. As for our studies about mobile robot control [20], they have given birth to the theory of stabilization of nonlinear systems via *time-varying continuous state feedback* and, even more recently, to a new approach of *practical stabilization* [47] for "highly" nonlinear systems.

3.3. Active perception

Keywords: *3D reconstruction, active perception, image processing, range sensing, sensors modeling.*

Participants: Ezio Malis, Patrick Rives, Selim Benhimane, Vincent Brandou, Christopher Mei, Alessandro Corrêa-Victorino, Nicolas Simond, Geraldo Silveira, Andrew Comport.

No autonomy is possible without the perception of the surrounding environment. Perception involves data acquisition, via sensors endowed with various characteristics and properties, and data processing in order to extract the information needed to plan and execute actions. In this respect, the fusion of complementary information provided by different sensors is a central issue. Much research effort is devoted to the modeling of the environment and the construction of maps used, for instance, for localization estimation and motion planning purposes. Another important category of problems concerns the selection and treatment of the information used by low-level control loops. Much of the processing must be performed in real-time, with a good degree of robustness so as to accommodate with the large variability of the physical world. Computational efficiency and well-posedness of the algorithms are constant preoccupations. Low-level sensor-based control laws must be designed in accordance with the specificities of the considered sensors and the nature of the task to be performed. Complex behaviors, such as robot navigation in an unknown environment, are typically obtained by sequencing several such elementary sensor-based tasks. The sequencing strategy is itself reactive. It involves, for instance, the recognition and tracking of landmarks, in association with the construction and updating of models of the robot's environment. Among the multitude of issued related to perception in Robotics, ICARE has been addressing a few central ones with a more particular focus on visual and range sensing.

3.3.1. Sensor modeling and fusion

The important variability of the environment (e.g. large variations in the lightning conditions for outdoor artificial vision) is one of the elements which make robustness a key issue in Robotics. The combination of realistic sensor models and sensor fusion is an answer (among many others) to this preoccupation.

- *Realistic sensors models :* The simple models commonly employed to describe the formation of sensor data (i.e. pinhole camera, Lambertian reflection...) may fail to accurately describe the *physical* process of sensing. Improvement in this respect is possible and useful [48], [42].
- *Sensor Fusion :* The integration of several complementary sensory information can yield more reliable constructions of models of the environment and more accurate estimations of various position/velocity-related quantities. This can be done by mixing proprioceptive and exteroceptive data. Sensor fusion is an important, still very open, domain of research which calls for more formalization.

3.3.2. Robust tracking of landmark

Mobile robots move in complex, often dynamic, environments. To build models of the environment, or to implement sensor-based control laws, it is often useful to extract and track landmarks from sensory data. In particular, the localization of the robot in the environment is greatly simplified. Landmark tracking is done in real-time, and it should be robust with respect to apparent modifications (occlusions, shadows,...) of the environment. *Outliers rejection* in landmark tracking, and *parameter estimation and filtering* involved in robot localization, are two complementary aspects of a generic problem.

- *Outliers rejection :* Outliers, which do not correspond to anything in the physical world, have to be filtered out as much as possible. Standard Least-Squares or Kalman filtering techniques are inefficient in this respect, and they can in fact produce catastrophic results when the rate of outliers increases. Robust estimators (voting, M-estimators, Least Median Squares,...) have been specifically developed to solve this problem.
- *Parameter estimation and filtering :* Extended Kalman Filtering techniques (EKF) are commonly used in robotics to deal with noisy sensory data. However, in some cases, depending for instance on the noise distribution characteristics, the stability of such a filter can be jeopardized. An alternative consists in using *bounded-error methods* [49] whose stability is independent of the noise distribution. These techniques have been successfully applied to robot motion estimation when using a laser range finder [24].

3.3.3. Sensor-based control

Perception aspects have to be taken into account very early at the task planning level. An outcome of this planning phase is the design and selection of a set of sensor-based control loops in charge of monitoring the interaction between the robot and its environment during the task execution [16]. Another one is the specification of external events the occurrence of which signals, among other things, when the system's actions have to be modified by replacing the currently running sensor-based control by another one (reactive aspect). In both cases, it matters to use perception information so that the success of the resulting control strategy is not jeopardized when the task execution conditions are slightly modified (robustness). In ICARE, we often use the formalisms of task-functions and virtual linkages [19] for the design of such sensor-based control laws, each of them corresponding to an elementary sensor-based action (wall following, for example). These formalisms are general so that they apply to various sensors used in Robotics (odometry, force sensors, inertial navigation systems, proximetry, local vision).

3.4. Robot navigation and guidance

Keywords: *SLAM*, *localization*, *multisensory cooperation*, *reactive navigation*, *sensor-based planning*, *vision and range sensors*.

Participants: Patrick Rives, Ezio Malis, Alessandro Corrêa-Victorino, Nicolas Simond, Christopher Mei, Geraldo Silveira, Andrew Comport.

Many application fields (transportation, individual vehicles, aerial robots, observation underwater devices,...) involve navigation issues, especially when the main goal is to make a robotic vehicle move safely in a partially unknown environment. This is done by monitoring the interaction between the vehicle and its environment. This interaction may take different forms : actions from the robot (positioning with respect to an object, car parking maneuvers,...), reactions to events coming from the environment (obstacle avoidance,...), or a combination of actions and reactions (target tracking). The degree of autonomy and safety of the system resides in its capacity to take this interaction into account at all the task levels. At a higher level, it also requires the definition of a planning strategy for the robot actions during the navigation [45]. The spectrum of possible situations is large, ranging from the case when the knowledge about the environment is sufficient to allow for off-line planning of the task, to the case when no information is available in advance so that on-line acquisition of a model of the environment during an initial exploration phase is required [41].

The problems of navigation addressed by the ICARE team concern both indoor and outdoor environments (urban-like). The approaches that we develop are based on three ideas : i) combine the information contained in proprioceptive and exteroceptive sensory data, ii) use sensor-based control laws for robot motion and also to enforce constraints which can in turn be used for the localization of the robot and the geometrical modeling of the environment, and iii) combine locally precise metrical models of the environment with a global, more flexible, topological model in order to optimize the mapping process [24], [25].

3.4.1. Exploration and map building

Given a set of sensory measurements, scene modeling (or map building, depending on the context of the application) consists in constructing a geometrical and/or topological representation of the environment. When the sensors are mounted on the mobile robot, several difficulties have to be dealt with. For instance, the domain in which the robot operates can be large and its localization within this domain often uncertain. Also, the elements in the scene can be unstructured natural objects, and their complete observation may entail moving the sensors around and merging partial information issued from several data sequences. Finally, the robot positions and displacements during data acquisition are not known precisely. With these potential difficulties in mind, one is brought to devise methods relying almost exclusively on measured data and the verification of basic object properties, such as the rigidity of an object. The success of these methods much depends on the quality of the algorithms used (typically) for feature extraction and/or line-segmentation purposes. Also, particular attention has to be paid to avoid problems when the observability of the structure eventually becomes ill-conditioned (e.g. pure rotation of the camera which collects the data). When no prior knowledge is available, the robot has to explore and incrementally build the map on line. For indoor environments, this map can often be reduced to polygonal representations of the obstacles calculated from the data acquired by the on-board sensors (vision, laser range finder, odometry ...). Despite this apparent simplicity, the construction and updating of such models remain difficult, in particular at the level of managing the uncertainties in the process of merging several data acquisitions during the robot's motion. Complementary to the geometrical models, the topological models are more abstract representations which can be obtained by structuring the information contained in geometrical models (segmentation into connected regions defining locations) or directly built on-line during the navigation task. Their use infers another kind of problem which is the search and recognition of connecting points between different locations (like doors in an indoor scene) with the help of pattern recognition techniques.

3.4.2. Localization and guidance

In the case of perception for localization purposes, the problems are slightly different. It matters then to produce and update an estimation of the robot's state (in general, its position and orientation) along the motion. The techniques employed are those of filtering. In order to compensate for drifts introduced by most proprioceptive sensors (odometry, inertial navigation systems,...), most so-called hybrid approaches use data acquired from the environment by means of exteroceptive sensors in order to make corrections upon characteristic features of the scene (landmarks). Implementing this type of approach raises several problems about the selection, reliable extraction, and identification of these characteristic features. Moreover, critical real time constraints impose the use of low computational cost and efficient algorithms.

In the same way as it is important to take perception aspects into account very early at the task planning level, it is also necessary to control the interaction between the robot and its environment during the task execution [16]. This entails the explicit use of perceptual information in the design of robust control loops (continuous aspect) and also in the detection of external events which compel to modify the system's actions (reactive aspect). In both cases it matters to make more robust the system's behavior with respect to the variability of the task execution conditions. This variability may arise from measurement errors or from modeling errors associated either with the sensors or the controlled systems themselves, but it may also arise from poor knowledge of the environment and uncertainties about the way the environment changes with time. At the control level, one has to design feedback control schemes based on the perceptual information and best adapted to the task objectives. For the construction of suitable sensor-based control laws one can apply the task-function approach which allows to translate the task objectives into the regulation of an output vector-valued function to zero. Reactivity with respect to external events which modify the robot's operating conditions requires detecting these events and adapting the robot's behavior accordingly. By associating a desired logical behavior with a dedicated control law, it becomes possible to define *sensor-based elementary actions* (wall following, for instance) which can in turn be manipulated at a higher planning level while ensuring robustness at the execution level. The formalisms is generic enough to suggests that they can be applied to various sensors used in Robotics (odometry, force sensors, inertial navigation systems, proximetry, local vision,...).

3.5. Means of experimentation

Experiments are currently conducted on two test-beds.

- *ANIS Mobile indoor platform*
  This platform consists of a mobile base with a six degree-of-freedom manipulator arm mounted on it. It is also equipped with a belt of eight ultrasonic sensors, a camera attached to the manipulator's end-effector, an omnidirectionnal camera, and a laser range finder located on top of the first manipulator's articulation.
- *CyCab Outdoor electrical car*
  Since May 2001, the *Visa* team, directed by P. Rives, is in charge of an experimental platform at INRIA Sophia-Antipolis based on two instrumented electrical cars of the *CyCab* family and destined to project-teams wishing to validate their research in the domain of *vehicles for the future*. The project ICARE is further involved via two PhD research studies supported by the European Project *CyberCars* on automatic navigation and driving. *CyCabs* are also used as experimental testbed in two national projects : an interdisciplinary CNRS/INRIA robotics program called ROBEA: *BODEGA Safe Navigation in Urban Environments* and a Predit project called *MobiVIP*.

4. Application Domains

4.1. Panorama

Besides the traditional domain of robot manipulation, Robotics offers many other application possibilities entailing the use of mechanical systems endowed, to some extent, with capacities of autonomy and capable of operating in automatic mode : intervention in hostile environments, long range exploration, mobile robots, automatic driving, observation and surveillance by aerial drones,... without forgetting emerging and rapidly expanding applications in the domains of robotic domestic appliances, toys, and medicine (surgery, assistance to handicapped persons, artificial limbs,...). The recent explosion of applications and new scientific horizons is a tangible sign that Robotics, at the crossway of many disciplines, will play a ubiquitous role in the future of Science and Technology.

ICARE's approach, for the design of autonomous systems, is a bottom-up one consisting in exploring the possibilities offered by low-level sensor-based control loops, of the reflex type (by analogy with biological systems), and their combination for the realization of complex tasks, prior to addressing higher levels of control.

The project is also involved at this application level through national and international collaborations. These collaborations concern more specifically the domain of future transportation systems, with a participation in the European Project CYBERCARS and the national Predit Project MOBIVIP, a project for the development of surveillance robots, in partnership with the company ECA in Toulon, and a project about observation aerial drones, in partnership with the Superior Technical Institute (I.S.T.) in Portugal and the Laboratory of Robotics and Computer Science of Campinas (CenPRA) in Brazil.

4.2. Automatic driving

Keywords: *control of car-like vehicles*, *navigation*, *sensor-based control*, *sensory fusion*.

Participants: Claude Samson, Patrick Rives, Ezio Malis, Pascal Morin, Selim Benhimane, Nicolas Simond.

The development and management of transportation means, in urban and inter-urban zones, has become a major issue for most industrialized countries. Several countries (United States of America, Japan, Holland, Germany,...) have already set in place important research programs aiming at proposing alternatives to the existing modes of transportation. The objectives are the reduction of ecological nuisances (pollution, noise, downtown traffic congestion,...) and the optimization of the adequation between the means of transportation, circulation infrastructures, and safety (electrical car-sharing services in urban environment, automatic driving on freeways).

A previous cooperative action called Praxitèle, which ended in 1997, has allowed the validation of a certain number of concepts and the design of an electrical vehicle prototype, called CyCab, a dozen examples of which have been made and are disseminated over the different Inria sites. In view of supporting the applicative domain of *Transportations for the future*, the site at Sophia-Antipolis has acquired one of these vehicles in 2001 and created the “action of valorisation” Visa under the leadership of P. Rives. The scope of this action is transversal to the research done in the project-teams and consists of setting in place the experimental means necessary to validate research results in the domain of transportation for the future. ICARE participates in this venture via two PhD thesis which have received financial support from the European Projects CYBERCARS and CYBERMOVE.

The first subject of research concerns the study of control methods for a system composed of two car-like vehicles (a leading vehicle and a tracking one) in order to perform different tasks (road following, parking maneuvers,...) according to several operating modes (coordinated and robust control of both vehicles, manual driving of the first vehicle and automatic tracking of this vehicle by the second one,...). Later, it will be possible to generalize the study to trains of more than two vehicles, with extensions to vehicles mechanically hooked together (trucks with trailers, for instance).

The second subject addresses autonomous and semi-autonomous navigation (assistance to driving) of the CyCab by using information data provided by visual or telemetric sensors. This is closely related to the problem of a vehicle moving in an urban environment with its specific aspects of localization, path planning and following, subjected to stringent safety constraints (detection of pedestrians and obstacles) within large and evolutive structured environments. Since the end of the CYBERCARS and CYBERMOVE, this activity is carrying on in the context of the national Predit Project MOBIVIP.

4.3. Indoor Robotics

Keywords: *SLAM*, *reactive navigation*, *scene modeling*, *sensor-based navigation and control*.

Participants: Patrick Rives, Alessandro Corrêa-Victorino, Christopher Mei.

In relation to the technological evolution of sensors and means of computation, new fields of application for indoor robotics have recently emerged, ranging from low-cost domestic applications, such as autonomous vacuum cleaners, to more exacting ones in terms of robustness and performance, like tour guide robots in exhibitions or surveillance indoor robots. For such applications, the robot must be able to incrementally build and update representations of its changing surroundings and move safely among unforeseen obstacles.

In the ICARE team, we address the canonical problem of the simultaneous localization and mapping of a large unknown indoor environment. New developments are currently carried out with the company ECA in the context of the *Programme d'Etude Amont: MiniROC* funded by the *DGA (Délégation Générale à l'Armement)*.

4.4. Aerial robotics

Keywords: *airship*, *drone*, *modeling and control of aerial vehicles*, *visual servoing*.

Participants: Patrick Rives, Ezio Malis, Samuel Bueno [CenPRA de Campinas (Brazil)], Geraldo Silveira [CenPRA de Campinas (Brazil) from 11/01/04 PhD student], José Raul Azinheira [IST de Lisbonne (Portugal)].

Our collaboration with the CenPRA of Campinas and IST of Lisboa participates in the general theme of designing and controling aerial vehicles (*drones*) for the realization of missions of surveillance and intervention, either in a completely autonomous mode or in a mixed (partly teleoperated) mode. Potential applications for such vehicles are numerous, either civilian (surveillance of forests, rural or urban zones, ecological reserves, roads, seashores,...) or military (observation, tactical support,...), and many countries (Sweden, Brazil, Portugal, Israël, United States of America,...) devote large budgets to it.

The project AURORA (*Autonomous Unmanned Remote Monitoring Robotic Airship*) led by the LRV/IA/CenPRA aims at the development of a blimp dedicated to observation. The main foreseen domain of application would be the study and surveillance of the environment. This blimp will be endowed with large capacities of autonomy in all classical phases of flight (taking off, stationary flight, cruising, and landing).

In parallel, the IST and OGMA in Portugal, and the RMCS (Cranfield University) in Great Britain, have developed, within the framework of a cooperative research program, a drone plane for civilian applications like fire prevention and the surveillance of coastal zones.

The problems, in terms of control, navigation, and other types of missions happen to be very close to the ones that we have studied a few years ago in the domain of navigation and control of submarine vehicles. Collaboration agreements on this theme were signed in 1999 between Inria, Brazilian CNPq, and Portugese ICCTI. This cooperation is continuing and promotes missions of exchange among the participants. At Inria, we are more particularly in charge of studying the contribution of visual servoing techniques for the automatisation of certain flight phases, such as stationary flight and landing, which necessitate a very precise control of the attitude and of the velocity with respect to the ground. The main difficulties concern the modeling and the control of aerial drones which reveal to be very nonlinear dynamical systems with a large spectrum of radically different flying modes and model specificities. The control methods developed in the project, which allow to robustly stabilize the attitude of a generic vehicle with respect to its environment, appear to be well adapted to this type of application. They have been tested in simulation and are currently being validated on the devices developed by our partners.

5. Software

5.1. Software

5.1.1. Specific software for experimental purpose

We are currently developing a three-stage software environment based respectively on Matlab, C++, and C. The Matlab stage is for quick prototyping and simulation of algorithms. A training student can rapidly use it. The C++ stage allows to pass from the simulation stage to a real experiment without much effort, thanks to a matrix calculus library conceived so as to minimize the modifications to be brought to the Matlab program. Finally, the C stage is needed for the real-time implementation of the algorithms on our robotic platforms.

5.1.2. Image processing

- ESM Tracking and Control Software has been implemented using the three-stage environment described above. The software allows the visual tracking and servoing with respect to planar objects. The software has been successfully tested on the Cycabs in a car platooning application. We are currently transferring it to the LRV/IA/CenPRA in Brazil.
- VPI VISION PROGRAMMING INTERFACE is a software for rapid prototyping of vision applications. It is based on the QT library (license GPL *GNU Public License* under *Linux*). It has been lent, for internal use, to the IFREMER's Robotics Center in Toulon.

6. New Results

6.1. Stabilization of mobile robots and of nonlinear systems

Keywords: *Lie group*, *asymptotic stabilization*, *manipulator arm*, *mobile manipulation*, *mobile robot*, *nonlinear system*, *practical stabilization*, *practical stabilization*, *task function*, *time-varying control*, *transverse function*, *underactuated system*.

Participants: Claude Samson, Pascal Morin, Doojin Choi, Matthieu Fruchard, Mauro Maya Mendez.

We are interested in the stabilization of controllable nonlinear systems which lose the property of being controllable when they are linearized at an equilibrium point. Wheeled mobile robots subjected to nonholonomic contraints belong to this category of systems. In the past, we have addressed this problem via the development of the theory of time-varying feedback control. In the last few years we have focused our research on a new control approach, that we have called the *Transverse Function* approach [11], [13], [12], with the objective of stabilizing asymptotically a set contained in an arbitrary "small" neighborhood of the state-point of interest (a type of practical stabilization), rather than stabilizing asymptotically the point itself –as we used to do. This objective is all the more natural that the point of interest may not be stabilizable. It may also seem less ambitious than the former one —when the point of interest is stabilizable—, since the asymptotic stabilization of a point implies that this point is practically stabilized. We believe that it is in fact complementary, more general (since it encompasses all point asymptotic stabilizers), and well suited to this class of nonlinear systems. For instance, it allows to better account for what can be done to reject additive perturbations acting on the system. This contributes to the enlargement of the range of applications that can be addressed by the control solutions so derived.

6.1.1. Control of underactuated mechanical systems

An important extension of the transverse function approach, initiated this year, concerns underactuated mechanical systems which, like nonholonomic vehicles, are locally controllable at zero velocity while their corresponding linear approximation is not. Examples of such systems are underactuated manipulators, hovercrafts, blimps in the absence of head wind, satellites subjected to actuation failure, and any other physical system which can be modeled by a second-order chained system. Feedback stabilization of these systems is also known to be particularly challenging, and few solutions to this problem have been offered until now. The aforementioned extension of the transverse function approach is not direct because the dynamical part of the system, which describes the way the system is underactuated and the action of dynamical coupling, and which also captures the controllability properties of the system, can no longer be overlooked. As a result, and unlike the case of fully actuated nonholonomic systems, the modeling of any underactuated system incorporates a drift vector field whose role is central to the control design. Although the transverse function control approach has not been developed for this class of systems in the first place, the derivation of new control solutions based on an extension of this approach will hopefully constitute an original contribution to nonlinear control theory with potential applications concerning a large spectrum of robotic devices.

Our initial efforts in this direction have focused on mechanical systems invariant on three-dimensional Lie groups such as $\mathbb{R}^3$, $SE(2)$ (isomorphic to $\mathbb{R}^2 \times S^1$), and $SO(3)$. This choice was motivated by the fact that the dynamical part of these systems, also of dimension three, is at the same time simple and representative of what can be done, in a second stage, for higher dimensional systems. More precisely, the model equations that we have considered are in the form:

$$\begin{array}{rcl} \dot{g} & = & \sum_{i=1,2,3} X_i(g)\xi_i \\ \dot{\xi}_1 & = & u_1 \\ \dot{\xi}_2 & = & u_2 \\ \dot{\xi}_3 & = & a\xi_1\xi_2 \end{array}$$

with $g \in G$ (the "natural" Lie group associated with the system's kinematics) representing in general the position/orientation of the system, $\{X_i(g)\}_{i=1,2,3}$ a basis of the Lie group algebra, ξ the corresponding vector of velocity intensities, $u_{1,2}$ the two control inputs (i.e. external forces and torques produced by actuators in order to control the system's position and orientation), and a a "coupling" constant which has to be different from zero for the system to be locally controllable. A particular case is the second-order chained system for which $G = \mathbb{R}^3$, $X_1(g) = (1, 0, g_2)^T$, $X_2 = (0, 1, 0)^T$, $X_3 = (0, 0, 1)^T$, and $a = -1$.

The control objective that we have addressed is the practical stabilization of *any* (not necessarily feasible) smooth reference trajectory $g_r(t)$ in the configuration space, with the complementary constraints of i) keeping all velocities and control inputs bounded and ii) having them converge to zero when $g_r(t)$ converges to a fixed configuration. These constraints are important because they are physically meaningful and also because they significantly reduce the set of "admissible" solutions. For instance, the first one eliminates (simple) solutions obtained by discarding diverging coupling effects at the dynamical level, whereas the second one is a criterion to discriminate solutions which ensure the boundedness of all velocities but, for some of them, fail to yield convergence to zero when such a convergence is possible.

Solutions to this control problem, derived by extending the transverse function approach, are reported in [38], [33]. However, the issue of convergence of the system's velocities to zero in the case of a fixed desired configuration is not addressed in these papers because it is still a pending question in the general case. Nonetheless, we have also made progress in this direction and are able to prove, by using various approaches (singular perturbation techniques, center manifold theory and averaging, Lyapunov techniques) whether a practical stabilizer has, at least locally, the desired property or not. In the particular case of the second-order chained system we can also prove that global convergence to zero (i.e. for all initial conditions) can be achieved by such a stabilizer, for a particular choice of the control gains. To be more precise, one shows that these properties can be deduced from the analysis of convergence to zero of two variables x_2 and x_3 satisfying the following equations (which characterize the *zero-dynamics* of the controlled system):

$$\begin{array}{rcl} \dot{\theta} & = & 2(-k_3 x_3 + (\frac{k_3}{b} - k_2)\sin(\theta) x_2) \\ \dot{x}_2 & = & -k_2 x_2 - \sin(\theta)\dot{\theta} \\ \dot{x}_3 & = & \cos(\theta)\dot{\theta} x_2 \end{array}$$

with b a strictly positive real number, and k_2 and k_3 strictly positive control gains. Local convergence (when initial values of $|\dot{\theta}|$, $|x_2|$, and $|x_3|$ are small enough) is ensured provided e.g. that $2k_3(1-b)/3b < k_2 < 2k_3/b$. The particular case when $k_3 = bk_2$ is the only one for which we have (so far) managed to prove global convergence to zero.

We are currently working on the generalisation of the control design to underactuated systems evolving on a Lie group of a higher dimension. $SE(3)$, which is isomorphic to $\mathbb{R}^3 \times SO(3)$, is of particular interest since it covers the case of all rigid bodies moving in the cartesian space. Another intriguing issue that we plan to address concerns the addition of gravity interaction terms to the system's dynamical equations. These terms are known to facilitate the design of controllers based on classical methods, because they usually render the linear approximation of the underactuated system controllable, and we would like to investigate their effects when the control is derived with the transverse function point of view. A further motivation comes from the fact that many aerial and underwater underactuated vehicles subjected to the gravity field often need it to operate properly.

6.1.2. Sensor-based control of non-holonomic mobile robots by the transverse function approach

The objective of this work is the development of sensor-based control methodologies for non-holonomic vehicles (unicycles, cars,...). We assume that the vehicle is equipped with a sensory system which provides data from which the posture of the robot with respect to a reference frame can be calculated. A typical example of such a system is Icare's mobile robot ANIS, equipped with a camera observing a rigid object with which a reference frame can be associated. In many applications however, both models of the sensor and the environment are inaccurate, so that the calculation of the robot's posture with respect to the reference frame cannot be precise. Our goal is to develop control methods for the stabilization of the vehicle's posture (i.e. position *and* orientation), which are robust against measurements uncertainties of this type.

For holonomic manipulator arms, it is well known that a rough knowledge of the signal function Jacobian at the desired configuration is sufficient to design feedback laws that guarantee the local asymptotic stability of this configuration. A possible way to design such control laws consists for example in using an estimation of the robot's posture, computed from the signal function Jacobian and the sensor output. We have studied the adaptation of this class of techniques to non-holonomic systems, in the framework of the transverse function approach which allows to design practical stabilizers for the tracking of arbitrary reference trajectories [12]. More precisely, we provide sufficient conditions on the robot's posture estimation error under which the design of practical stabilizers for the system can be achieved. These conditions are similar to those that can be derived for holonomic systems. They imply, in particular, that an (accurate enough) estimation of the signal function Jacobian at the desired configuration is sufficient to design (local) practical stabilizers. This result applies to both unicycle and car-like vehicles, and also addresses the case of a moving target.

The property of practical stability guarantees the convergence of the vehicle to a neighborhood of the desired configuration. When the target is fixed, it is also desirable to ensure in addition that the vehicle converges to a *fixed* final posture. We have also provided sufficient conditions on the signal function to guarantee this convergence property. These conditions are, however, more restrictive than the conditions derived for the practical stability property. They also depend on the class of vehicles considered (i.e. they are more restrictive for a car-like vehicle than for a unicycle). Extensive simulations suggest that convergence occcurs under much weaker conditions, although we have not yet been able to prove it analytically.

These results have been validated in simulation, and also on the team's unicycle-like robot ANIS.

6.1.3. Control of nonholonomic mobile manipulators

Our research on this topic corresponds to our participation in a three years' project, whose termination was programmed at the beginning of this year, involving two other robotics laboratories (LAAS-CNRS of Toulouse and LGP-ENI of Tarbes), within the national program ROBEA jointly supported by the CNRS and INRIA. The project's central theme was the control of robotic mixed mechanical structures composed of a holonomic manipulator arm mounted on a nonholonomic mobile base (like cranes).

We have pursued the study of the "simplified" control design methodology evoked in last year's report, based on the Task Function approach –at the manipulation task level– and the Transverse Function approach –to take care of the nonholonomy aspect of the problem via the minimization of a secondary cost. The soundness of the methodology has been validated via extensive simulations. A technical report [37] summarizes the results that we have obtained and M. Fruchard, who has been working on this subject for the last three years, has successfully defended his PhD thesis (with honors) in September [27]. An article has also been submitted for possible publication in the Int. J. of Robotics Research. While this temporarily concludes our research investigations on the subject, we are confident that application opportunities involving mobile manipulators will show up in the near future and lead us to come back to it.

6.2. Active perception

Keywords: *calibration*, *robustness to parametric uncertainties*, *sensor modeling*, *structure from motion*, *vision-based control*, *visual tracking*.

Participants: Ezio Malis, Patrick Rives, Selim Benhimane, Christopher Mei, Manuel Vargas [Universidad de Sevilla (Seville, Spain)], José-Raul Azinheira [Instituto Superior Tecnico (Lisbonne, Portugal)].

The achievement of complex robotic applications such as autonomous exploration of large scale environments, observation and surveillance by aerial robots, and medical robotics needs the integration of several research areas in sensor modeling, active perception, visual tracking and servoing. Several problems still have to be solved.

- To simplify the setup, it is preferable to integrate, as far as possible, research works in computer vision and robotic control in a unified framework. Our objective is to build a generic, flexible and robust system that can be used for a variety of robotic applications.
- To facilitate the transfer of control methods on different systems, it is preferable to design control schemes which weakly rely on “a priori” knowledge about the environment. The knowledge about the environment is reconstructed from sensory data.
- To get reliable results in outdoor environments, the visual tracking and servoing techniques should be robust against uncertainties and perturbations. In the past, lack of robustness has hindered the use of vision sensor in complex applications.

6.2.1. Sensor modeling

6.2.1.1. Central catadioptric calibration from planar grid

Many approaches to central catadioptric calibration have been devised recently. They mainly differ in the type of mirrors taken into account (hyperbolic or parabolic), the projection model which is used (skewness, alignment errors, ...), the available *a priori* information (for example, the knowledge of the mirror parameter), and the type of method (auto-calibration, grids, ...). Non-parametric [52] approaches have also been studied.

However most of the work on the subject is theoretical and often hardly applicable to real-world calibration. We have opted for a grid-based approach [53] due to its simplicity of use. With the unified projection model from Geyer and Barreto [44] [39] and by making the assumption that the assembly errors are small, we have obtained a projection model which is easily optimized while providing accurate results. We have also developed an open source implementation of it[1].

6.2.2. Robust tracking

A possible approach to the design of vision-based control schemes consists in using, for specific purposes, vision and control methods which have been worked out independently. With such an approach, system integration can be very difficult due to the high number of different methods for visual tracking and visual servoing. Instead of considering vision and control systems separately, we propose to unify, as much as possible, various research works done in computer vision and robotic control within a single framework [30]. Our objective is to build a generic, flexible, and robust system which can be used for a variety of robotic applications. A class of vision-based control techniques satisfying these requirements has been proposed in [6]. These techniques have been designed to control the situation of a robot end-effector relatively to rigid objects whose shape is arbitrary, without having to rely on a known CAD model of the objects. Theoretically, the “model-free” (i.e. object model-free) control laws proposed in [6] can deal with many different applications when geometrical primitives (points, lines..) can be extracted from the images. In practice, however, the design of effective visual tracking algorithms remains application dependent. For instance, feature-based visual servoing methods rely explicitly on feature detection and they do not apply when the object with respect to which control is performed is not endowed with the considered set of features. In such cases, template-basd methods lying on the direct use of the grey level data without assuming any geometrical structure on the images, seem more adapted.

6.2.2.1. ESM (Efficient Second-order Minimization

Real time visual tracking In [30], we have showed that a more general system can be obtained by integrating template-based visual tracking algorithms and model-free vision-based control techniques. The key issues for the integration of such tracking techniques in a generic real-time control system are the flexibility, efficiency, precision, and robustness of the tracking algorithm. Indeed, template-based visual tracking algorithms estimate the deformation parameters of a certain template between two frames by minimizing an error measurement based on image brightness. Explicit segmentation of features is not required and visual tracking applies to objects with generic shape and texture. The main contribution of this work is the unification within a

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[1] http://www-sop.inria.fr/icare/personnel/Christopher.Mei/ChristopherMeiPhDStudentToolbox.html

single framework of the ESM visual tracking method and of model-free visual servoing techniques. In order to perfrom real-time applications with non-dedicated hardware several improvements of the ESM visual tracking have been proposed: an efficient coarse-to-fine strategy (multiresolution strategy) and a sub-sampling strategy. We have also proved that it is possible to impose euclidean constraints between the tracked planes or constraints on the movement of the camera. For example, figures 1-a and 1-b show three different planes tracked simultaneously under the constraint that the planes belong to a rigid scene. Figures 4-a and 4-b show the difference between the odometry reconstruction, considered as ground truth, and the values obtained from the tracking of the templates of the figures 1-a and 1-b. Along a path exceeding 6 meters in length the maximum translation error is 12 cm and the maximum rotation error is 1.6 degrees.


a) First image of a tracking sequence b) Image 1000 of a tracking sequence

Figure 1. Homography-based tracking for central catadioptric cameras

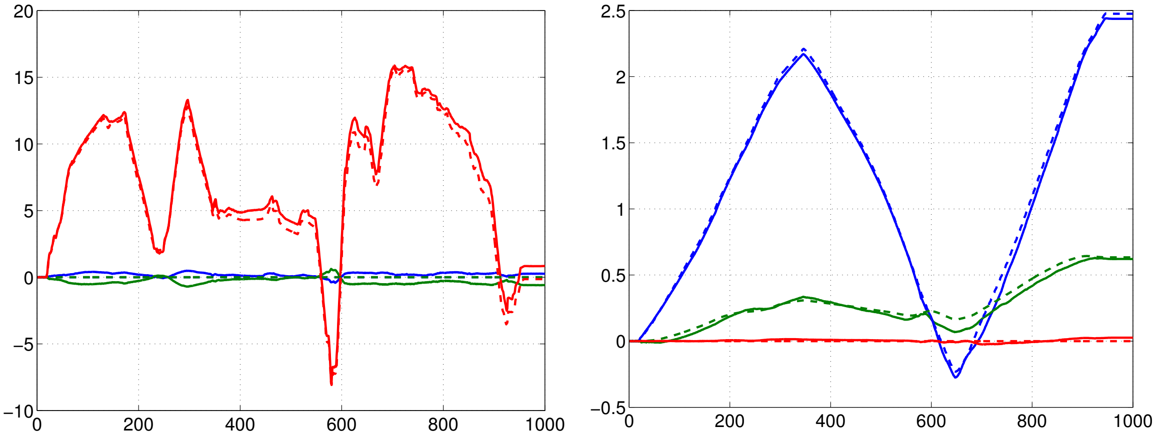
6.2.2.2. Homography-based tracking for central catadioptric cameras

Tracking is a fundamental step for various computer vision applications but very few articles based on the use of catadioptric systems are available. [40] is one of them. However, this approach proposed in this paper is limited to tracking straight lines using a contour-to-point tracker in order to avoid the problem of quadric-based catadioptric line fitting. A difficulty associated with these devices comes from the non-linear projection model resulting in changes of shape in the image. This basically precludes the direct use of methods such as KLT (see Fig. 3-a and Fig. 3-b). Parametric models, such as those involved in homography-based approaches, are well adapted to this problem. By extending the results on ESM tracking presented in [1] we have obtained a fast generic algorithm. The motion estimation calculated from the homography decomposition is also precise. More recently, we have been able to impose Euclidean constraints between the tracked planes and estimate the normals. This has improved the precision further. Figures 4-a and 4-b show the difference between the odometry reconstruction, considered as ground truth, and the values obtained from the tracking of the templates in figures 3-a and 3-b. Work is currently undertaken to use the tracking for the partial 3D reconstruction of a scene from a monocular sequence [46].

6.2.3. Sensor-based control

6.2.3.1. Robust visual servoing :

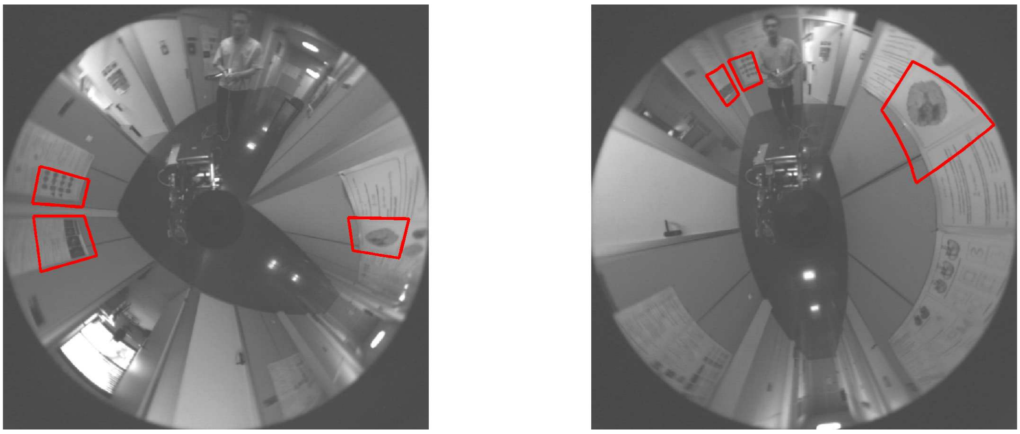
Visual servoing can be stated as a non-linear output regulation problem. The output is the image acquired by a camera mounted on a dynamic system. The state of the camera is thus accessible via a non-linear map. For



a) Rotation estimate (the odometry was used as ground truth)

b) Translation estimate (the odometry was used as ground truth)

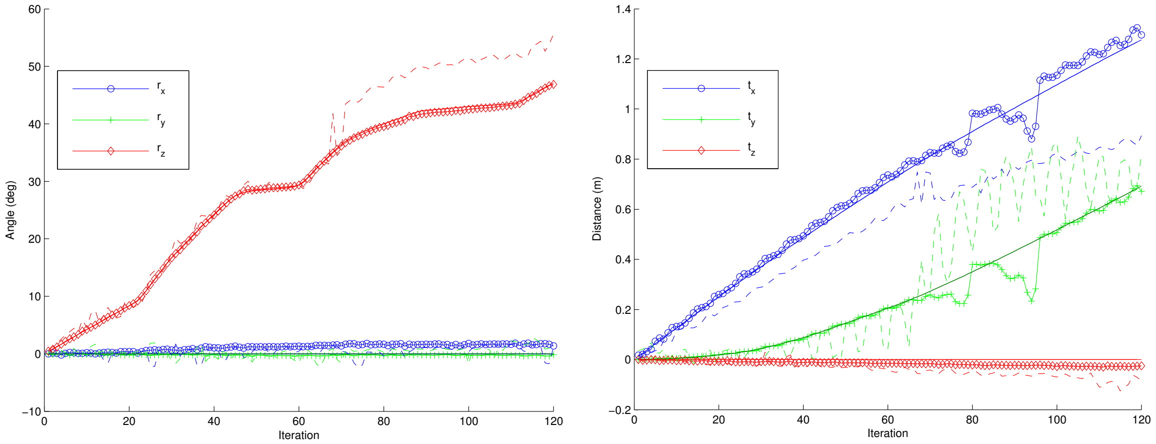
Figure 2. Comparison between odometry and visual trajectography



a) First image of a tracking sequence

b) Image 120 of a tracking sequence

Figure 3. Homography-based tracking for central catadioptric cameras



a) Rotation estimate (the odometry was used as ground truth)

b) Translation estimate (the odometry was used as ground truth)

Figure 4. Comparison between odometry and visual trajectography

this reason, camera positioning tasks have been defined by using the so-called teach-by-showing technique. With this technique, the camera is moved to a reference position and the corresponding reference image is stored. Then, starting from a different camera position, the control objective is to move the camera so that the current image finally coincides with the reference one. A solution to the control problem involves the processing of output measurements in order to design a non-linear state observer. This can be done using several output measurements. A difficulty is that, when considering real-time applications, one should process as few observations as possible. In the literature, authors have built non-linear state observers using additional *a priori* information (the normal to the plane, vanishing points, ...). In this case only the current and the reference observations are needed. On the other hand, we would like to perform vision-based control without having to rely on *a priori* information in order to increase its robustness. To this purpose, more observations are needed. We have thus defined a new control objective in order to move the camera with a bounded error and obtain the information which allows the state observer to perform well [35].

From these results, we have found that a positioning task can be performed without the explicit estimation of the camera pose. We have subsequently proposed a visual servoing method which does not rely on any measurement of the 3D structure of the observed target (i.e. the normal to the plane in the case of a planar object). Only visual information measured from the reference and the current image are needed to compute the task function (isomorphic to the camera pose) and the control law applied to the robot. The control law is designed in order to make the task function converge to zero. Proofs of the existence of the isomorphism between the task function and the camera pose and of the local stability of the control law have been worked out. The experimental results, obtained with the 6 d.o.f. manipulator of ANIS, show the advantages of the proposed method with respect to other approaches. The vision-based control method has also been generalized to the case of central catadioptric cameras (including omnidirectional cameras).

6.2.3.2. Controlling the trajectories of a stereo rig with camera-invariant visual servoing

Our goal is to develop a methodology based on a stereo vision system to obtain quantitative measurements for a 3D reconstruction of underwater structures. To this aim, we have studied how visual servoing techniques could be used to improve on the reconstruction of 3D objects. The images used for the reconstruction are acquired from a submarine navigating above the seafloor at a fixed and stable altitude. The camera is carried by a 6 DOF manipulator arm mounted on the vehicle. The images are subjected to several constraints related to the underwater environment. First, the observed scenes are not known in advance, and the objects reconstructed from these scenes have a random texture and form. We only know that the objects are rigid and that they are roughly vertically shaped. Refraction combined with the presence of particles, light absorption, and other lighting related problems considerably alter the quality of the images. From noisy images and a model of the object with many unknown parameters, it is very difficult to obtain a precise 3D reconstruction. The idea is thus to reduce the number of unknown parameters in the reconstruction computation. This produces a faster algorithm, better adapted to time-dependent applications as in robotics. In order to gather more information, images are acquired at regular intervals, following a predefined trajectory. Visual servoing is performed with a pair of stereo cameras mounted on the manipulator arm effector. We have showed that the stereo rig geometry determines the trajectory around the object and the number of pictures needed for its reconstruction. In our case, the stereo rig is equipped with two different underwater cameras. The first one is fixed while the other one is mounted on a pan & tilt turret, and the intrinsic parameters are not the same for the two cameras. Moreover these parameters depend on the characteristics of the underwater environment, like the optical index, which varies according to temperature, salinity, pressure, and wavelength. However, when different cameras are used the intrinsic parameters should be determined via a calibration process. The underwater vehicle used for the final experiments can dive down to 6000 meters. At this depth it is very difficult to use a camera calibration pattern. This leads to using autocalibration techniques, with new constraints on the robot displacement. Subsequently, we have implemented a visual servoing method which is invariant to camera intrinsic parameters [8]. The proposed visual servoing scheme has been validated by experimenting on two different robots: the robot ANIS at INRIA and the robot MAESTRO at IFREMER. Figures 5-a and 5-b show, as an example, a visual servoing experiment carried out with a stereo system mounted on the robot ANIS.

a) The stereo system mounted on the robot ANIS

b) Visual servoing experiment

Figure 5. Active stereo reconstruction with camera invariant visual servoing

6.3. Robot navigation and guidance

Keywords: *aerial robotics, safe navigation for a mobile robot, simultaneous localization and mapping (SLAM), vision based platooning.*

Participants: Patrick Rives, Ezio Malis, Alessandro Corrêa-Victorino, Christopher Mei, Nicolas Simond, Selim Benhimane, José-Raul Azinheira [Instituto Superior Tecnico (Lisbonne, Portugal)], Samuel Bueno

[Information Technology Institute (Campinas, Brésil)], Geraldo Silveira [Information Technology Institute (Campinas, Brésil)].

Performing high level robotics tasks such as robot navigation in an unknown environment or autonomous landing for an aerial vehicle, need to exploit the algorithms of perception at different levels from the low level control loops up to the task planning strategies. In the Icare team, two main issues are currently addressed :

- Localization, navigation and map building both in indoors and outdoors environments. In this topic, we are interested by developping robust approaches which allows a robot to safely navigate in unknown, large environments. A central point concerns the transition from the local perceptions acquired by the robot during the exploration to a not biased and consistent global map.
- Automatic guidance for mobile robots. Here, we address the problem of guiding a mobile robot with respect to features extracted from the environment.

6.3.1. Localization, navigation and map building

6.3.1.1. SLAM in indoors environments

After more than two decades of intense research, the SLAM (*Simultaneous Localization And Mapping*) problem remains largely open. Our past contributions on the subject are summarized in previous activity reports, and in [24], [25]. The indoor mobile robot that we consider is equipped with a laser scanning device which produces a planar cross section of the environment. The exploration method is purely reactive, in the sense that it does not rely upon a preliminary trajectory planning procedure, and it guarantees a safe navigation in the free space of the environment. Reactive sensor-based navigation tasks and closed loop control laws are derived by using information gathered while the robot moves and progresses in its workspace. The closed-loop sensor-based control is designed so as to guarantee, along the exploration process, path-following error bounds that are independent of the distance covered by the robot. A model of the environment is built, based on an initial hybrid (metric and topological) representation which is updated and further refined during the exploration of the environment. The robot is precisely localized, in a set of local metric maps, when arriving in the vicinity of known predefined locations and objects in the environment. When it navigates between two such places, a topological description of the environment still provides a coarse localization.

Our framework has been successfully validated on our experimental mobile robot ANIS. New developments are currently carried out in the context of the *Programme d'Etude Amont: MiniROC* funded by the *DGA (Délégation Générale à l'Armement)*. Within this program, ICARE is in charge of the localization and mapping workpackages.

The activities conducted during this year aim at increasing the robustness and consistency of the model of the environment built during the exploration task. Our efforts have focused on two main issues : the optimization of the global map to solve the *loop closing problem*, and the improvement of the local perception in order to increase the robustness in the reactive navigation tasks.

The loop closing problem : Following the hybrid geometrical/topological representation presented last year, the global map is structured as a set of geometric *places* (where the robot is localized with metric precision) connected each other by a global topological model (for which the localization is performed in a semantical way). However, the lack of a precise metrics between the different places introduces *inconsistencies* on the global model when the robot returns to a place previously explored. This is often referred as the loop closing problem in the SLAM approach. To address this issue, we have proposed in [36] an optimization technique based on a semi-rigid modeling of the environment : the topological connections between places are modeled as *elastic constraints* while the geometrical structures at the places are modeled as *rigid constraints* (figure 6-left).

The optimization process starts when the robot detects its returning to a place already visited. The minimization of a global energy function allows us to iteratively adjust the position and orientation of each place involved in a cycle of the topological graph, under the constraint that the local rigidity of each place is preserved. Figure 6-right shows the result of the optimization process applied to the mapping of an

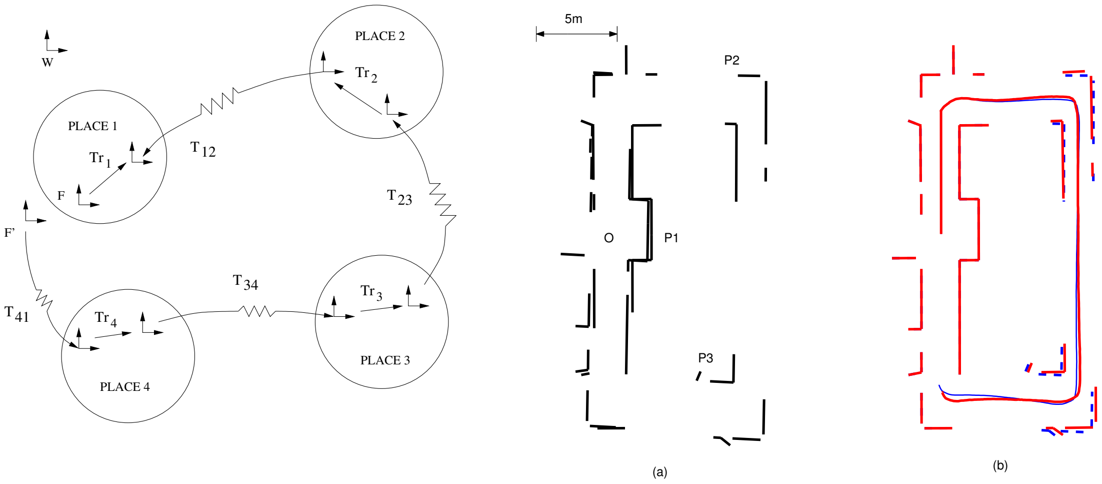


Figure 6. (left) the global semi-elastic system to be minimized, formed by rigid constraints, themselves connected by elastic constraints. (right)(a) The geometrical model of the three places before the fusion of place 1 with a fourth place under construction; (b) The result of the optimization process on the global hybrid model.

environment composed of three places. The robot explores the environment starting from the *O* position in *Place 1*. It maps places 2 and 3 and the the cycle is closed after returning to place 1.

Local navigation-based representation from laser scans : In the SLAM approach developped in the Icare project, the navigation of the robot is expressed as the realization of reactive navigation tasks defined on the local environment [24], [25]. These navigation tasks are performed by sequencing sensor-based control tasks relying on a local model built on-line from the data produced by a laser scanner device. The safety of the robot during its displacements and the success of the exploration are closely related to the consistency of the local model used by the navigation tasks. Due to artefacts and occlusion phenomena, the crude data provided by the laser scan is not reliable enough. We then define a *dynamic extended local model* which is a combination of recent past, present, and near future-predicted information from the robot surroundings. This dynamic extended local model cannot result from a classic filtering technique (like Kalman filtering) because the topological aspect of the local environment must be preserved to cope with the Voronoï representation which underlies the navigation tasks. A preliminary navigation-based representation based on the laser scans is currently under development (figure 7). Next, we expect to robustify this representation by merging laser and omnidirectional vision data.

6.3.1.2. Accurate localization of a car-like vehicle in an urban environment

The robust localization of a vehicle in an urban environment remains one of the main challenges for autonomous navigation inside dense urban environments. Accurate localization using a GPS is often unreliable due to the loss of visibility of the satellites, or artefacts induced by multiple paths propagation. To overcome these limitations, we are developing a vision-based approach to estimate the vehicle displacements by using an on-board weakly calibrated stereovision system.

The stereo-vision system makes it possible to cope with the complexity of the urban scenes (pedestrians, vehicles). Our method [23] exploits the fact that the features induced by dynamic obstacles do not verify the homographies linking the different views of the main planes in the scene (road, frontages). This year, our work has consisted in improving the robustness of our trajectography method w.r.t. various urban traffic conditions. This has been done by using the super-homography computation to take into account the epipolar and temporal constraints between the features coordinates detected in several views

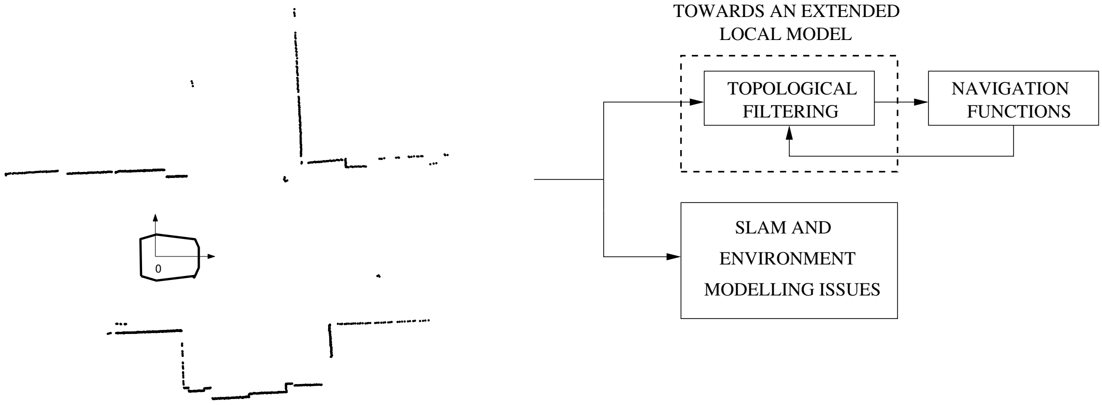


Figure 7. Development of an extended local model

In the specific context of an urban environment, a 2.5 D modeling can be performed by using the fact that the frontages of buildings are mainly composed of vertical planes. The frontages are structured areas where several corners and edges can be extracted. Also, the method previously developed for a road plane is easily transposed to the case of vertical planes. We show in Fig. 8 the result of super-homography computation applied to the three main planes in the observed scene. The vertical planes are first segmented according to the "canyon" model applied to the environment after the road area has been detected. The detection of features which do not belong to a main plane (i.e. which do not verify the homography constraint) allows for the identification of new regions labelled as obstacles.

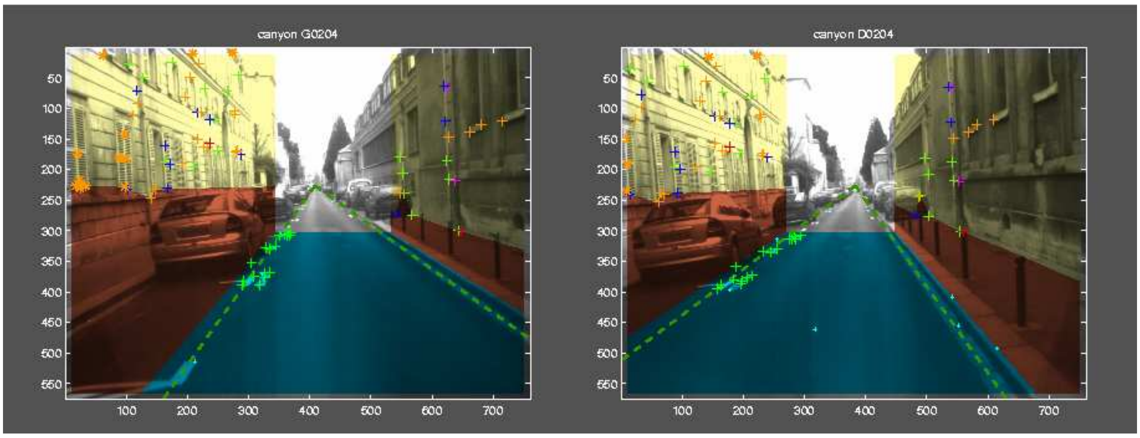
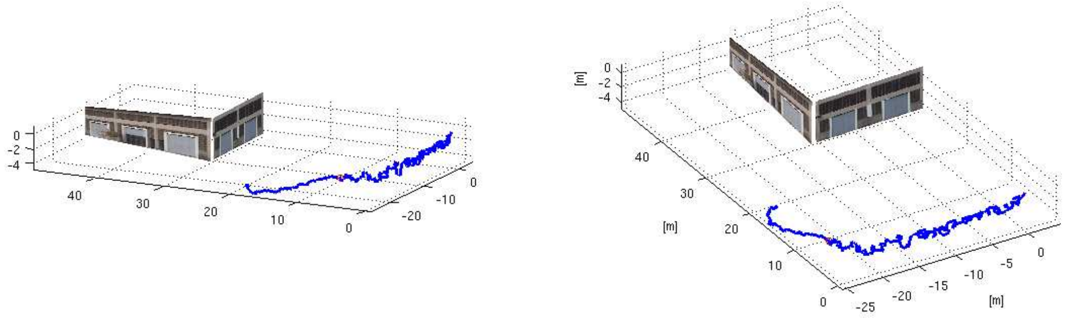


Figure 8. the modeling of urban canyons with three main planes (two vertical frontages (yellow) and the road plane (blue)) allows for a robust segmentation of the static scene. The observed features which do not belong to these planes are located in the image in the red masks and are viewed as obstacles.

6.3.2. Automatic guidance for mobile robots

6.3.2.1. Vision-based trajectory tracking over unknown, unstructured, large-scale scenes

The use of visual information to control dynamic systems via feedback has been widely generalized during the last decade. Several vision-based controllers have been proposed by the robotics community: model-based and model-free strategies, hybrid approaches, techniques based on motion, independent of the internal camera parameters, epipolar-geometry driven, amongst many others. In all cases, the control objective of visual servoing systems is to drive the robot from an initial pose back to a reference (desired) pose, by using appropriate information extracted from image data. Generally, those systems are designed to work well when the initial pose belongs to a small neighborhood of the desired one. The aim of our research work is to proposes a new vision-based control framework in order to handle model-free large-scale scenes for which the desired pose has never been attained by the robot and the desired image is not available. It is important to remark that existing visual servoing techniques do not apply in this context. The unknown rigid scene (i.e. the 3D model is not available) is represented as a collection of planar regions, which may enter and leave the field-of-view when the robot moves toward its distant goal. A novel approach to detect new planes that enter the field-of-view, robust to large camera calibration errors, has been worked out. The resulting Extended 3D vision-based control technique is also based on an efficient second-order method for plane-based tracking and pose reconstruction. It has been validated by using simulated data with artificially created scenes, as well as with real images. As an example, figures 9-a and 9-b show the execution of a SLAM task involving motion along a building and using the ESM visual tracking algorithm [1]. The path covered by the camera is 40 meters long, and one of the facade of the building was not visible at the beginning.



a) First screenshot of the reconstruction b) Second screenshot of the reconstruction

Figure 9. SLAM with the ESM visual tracking

This work is done in collaboration with the Laboratory of Robotics and Vision at the CenPRA (Campinas, Brazil) and the Department of Mechanical Engineering at IST (Lisboa, Portugal). It is closely related to the AURORA project which aims at the development of an autonomous airship dedicated to civil observation and survey missions. This blimp will be endowed with large capacities of autonomy in all classical phases of flight (taking off, stationary flight, cruising, and landing) and it will be able to realize long range navigation in complete autonomous mode.

6.3.2.2. Vision-based Control for Car Platooning

A lot of research on automatic driving is currently done in laboratories working on Intelligent Vehicles, and a major issue concerns the platooning problem. A key point is the robust detection and tracking of the ahead vehicle. At the present time, the systems closest to being operational use distance sensors like radars or lidars. This kind of sensors has the advantage of providing measurements which can be directly exploited at the control level. Alternative or complementary sensors are linear, standard or omni-directional cameras. Although this type of sensor is, by nature, sensitive to weather and lighting conditions, they provide a rich information which can be exploited to robustify the algorithms. Also, recent developments on high dynamic range CMOS cameras specifically dedicated to automotive applications could provide real solutions in terms of robustness with regard to the lighting changing conditions. We have proposed a complete vision-based platooning approach running in an outdoor environment [31]. Visual tracking is performed by directly estimating the projective transformation (in our case a homography) between a selected reference template attached to the leading vehicle and the corresponding area in the current image. Figure 10-a gives an overview of the vision system based on the ESM visual tracking [1]. The relative position and orientation of the servoed car with regard to the leading one is computed by decomposing the homography. The control objective is stated in terms of path following in order to cope with the nonholonomic constraints on the vehicles. A virtual frame rigidly linked to the leading vehicle is defined, and the path tracking error is expressed in the Cartesian space using the relative pose computed through the data given by the camera at video rate. Figure 10-b shows a car-platooning experiment carried out with two Cycabs.

a) The vision system and the ESM visual tracking software

b) The platooning application

Figure 10. Vision-based Control for Car Platooning

7. Contracts and Grants with Industry

7.1. Project IST CyberCars

Keywords: *Urban vehicles, control, navigation*.

Participants: Guillaume Artus, Nicolas Simond, Pascal Morin, Patrick Rives, Claude Samson.

A new type of vehicle-sharing is emerging with the development of a new type of vehicle: the automated vehicle. Such a vehicle has automated driving capabilities on existing road infrastructures endowed with a minimal right-of-way feature, as in the case of dedicated bus-lanes. Several companies and research organizations have been involved in the last ten years in the development of these new vehicles named CyberCars.

The objective of the IST CyberCars project is to bring all European actors in this field together in order to compare practices, share some of the development effort, and progress faster. A major work carried concerns the development and testing of several key technologies for the enhancement of the existing systems. These technologies are involved in automated guidance, collision avoidance, energy management, fleet management, and the development of simple standard user interfaces. Icare participates in this program through two PhD's Thesis works funded by CyberCars. The titles of the thesis subjects are :

- « Application of the transverse function approach to the control of maneuvering nonholonomic vehicles » (G. Artus defended in May 2005).
- « Localisation and navigation of an electrical car in an urban-type environment », (N. Simond defended in July 2005).

7.2. Project MiniROC (ECA/DGA)

Keywords: *SLAM*, *Survey robot*, *indoor robotics*.

Participants: Patrick Rives, Alessandro Corrêa-Victorino, Christopher Mei.

This project concerns the on-line indoors environment modeling and localization of a mobile robot platform equipped with multiple sensors (laser range-finder, omnidirectional vision, inertial gyrometer, odometry). This is a typical SLAM (Simultaneous Localization And Mapping) problem based on sensory data fusion, complemented with control/navigation issues. New developments are currently carried out in the context of the *Programme d'Etude Amont: MiniROC* funded by the *DGA (Délégation Générale à l'Armement)*. Within this program, ICARE is subcontractor of the company ECA and is in charge of the localization and mapping workpackages.

7.3. Project MobiVIP (Predit3)

Keywords: *control*, *localization*, *navigation*, *urban vehicle*.

Participants: Patrick Rives, Ezio Malis, Nicolas Simond, Selim Benhimane.

The field of intelligent transport systems, and more specifically the development of intelligent vehicles with fully automated driving capabilities, is becoming a promising domain of application and technology transfer from robotics research. It also gives rise to new research themes, such as heterogeneous wireless communications. The MobiVIP project, following the "Automated Road Scenario", focuses on low speed applications (<30 km/h) in an open, or partly open, urban context. The level of automatisation can vary from limited driving assistance to full autonomy. In all cases, an accurate (< 1m) and frequently updated (10 Hz) localization of the vehicle in its environment is necessary. With the GPS (differential an/or dynamic RTK) it is now possible to reach such an accuracy in open environments, but the problem has not yet been solved in dense urban areas (urban canyon).

Another issue is the accurate localization, referenced to the ground environment, needed to implement autonomous driving control techniques. Research is currently very active in this field known as SLAM (Simultaneous Localization and Mapping) or CML (Concurrent Mapping and Localization) problem. In the MobiVIP project, an important effort is devoted to the use of on-board vision coupled with hybrided GPS data, for modeling the urban environment. Such a model is then used in automatic guidance by applying visual servoing techniques developed by the research partners.

Experiments are carried out on the CyCab, a small electric vehicle, equipped with stereo cameras, differential hybrided GPS and inertial sensors (gyrometer, odometers).

7.4. Project Themis (Ifremer)

Keywords: *3D reconstruction*, *Visual servoing*, *underwater scene*.

Participants: Ezio Malis, Patrick Rives, Vincent Brandou, Selim Benhimane.

The objective is to design an active stereovision head controlled via visual servoing techniques 6.2.3.2. This work, initialy funded by a research contract, is currently pursued in the context of a PhD thesis funded by the Ifremer Institute and the PACA region.

8. Other Grants and Activities

8.1. National Activities

8.1.1. CNRS research projects ROBEA

Participants: Patrick Rives, Ezio Malis, Selim Benhimane.

Icare participates in one research project within the interdisciplinary CNRS/INRIA robotics program called ROBEA: *BODEGA Safe Navigation in Urban Environments* (**2003-2005**). This project, deals with the autonomous navigation of a car in an urban environment using vision and GPS sensors. It is conducted in collaboration with university, CNRS research teams and other INRIA teams: LASMEA (Clermont Ferrand), UTC-HEUDIASYC (Compiègne), Germes (Limoges), Lagadic (Inria-Rennes), TexMex (Inria-Rennes).

8.2. International Activities

8.2.1. Joint research program INRIA/PAPESP

The project AURORA (*Autonomous Unmanned Remote Monitoring Robotic Airship*) led by the LRV/IA/CenPRA aims at the development of an airship dedicated to observation. Collaboration agreements on this theme were signed between Inria, Brazilian CNPq and FAPESP, and Portugese ICCTI. In such a context, Geraldo Silveira is carrying on a PhD thesis in the ICARE team with a funding from the national brezilian agency CAPES. In November 2005, Patrick Rives and Ezio Malis have spent two weeks in Campinas for the transfer of visual tracking methods developped in the ICARE team.

9. Dissemination

9.1. Involvement in the scientific community

- C. Samson is a member of the Reading Committee for the SMAI (Société de Mathématiques Appliquées et Industrielles) book Collection on “Mathematics and Applications”.
- Since June 2005, P. Rives is Associated Editor of the journal IEEE International Transaction on Robotics (ITRO)
- E. Malis has been a member of the Program Committee of the following conferences: ORASIS 2005, CVPR 2005, ICCV 2005,
- P. Rives has been a member of the Program Commitee of the following conferences: JNRR 2005, RFIA 2006, ICRA 2006,
- During one week in June 2005, P. Rives, E. Malis and S. Benhimane participated in the mid-term MobiVIP demonstrations taking place in Nancy.

9.2. International conferences

Icare’s researchers have presented their work at the following conferences:

- IEEE International Conference on Robotics and Automation (ICRA), Barcelona, Spain, April 2005.
- IMACS World Congress, Paris, July 2005.
- IEEE/RSJ International Conference on Intelligent Robots Systems (IROS), Edmunton, Canada, August 2005.
- IEEE Conference on Decision and Control and European Control Conference, Sevilla, Spain, December 2005.

9.3. National conferences

Icare’s researchers have presented their work at the following conferences:

- Des Images au 3D, SEE, Ensta Paris, June 2005.
- Journées Nationales de la Recherche en Robotique, Guidel, October 2005.

9.4. Activities of general interest

- C. Samson is a member of the “Bureau du Comité des Projets” and of the “Commission des Postes Associés” at INRIA Sophia-Antipolis”.
- P. Rives is a member of the “Comité de Suivi Doctoral de l’U.R. de Sophia Antipolis”.
- P. Rives is a member of the *61^{e} Commission de Spécialistes de l’Université de Nice - Sophia Antipolis*.
- P. Rives is in charge of the R&D action VISA promoting the development of applications in the field of the Intelligent Transport System (ITS).
- E. Malis is a member of the “Commission de Développements Logiciels de l’U.R. de Sophia Antipolis”.
- E. Malis is a member of the *61^{e} Commission de Spécialistes de l’Université Blaise Pascal - Clermont-Ferrand*.

9.5. Education Through Research

- *Ph.D. Graduates* :
  - G. Artus « Application of the transverse function approach to the control of maneuvering nonholonomic vehicles », Ecole des Mines de Paris, May 2005, supervisors : C. Samson, P. Morin.
  - N. Simond, « Localisation et navigation d'un véhicule électrique dans un milieu de type urbain », Université de Nice-Sophia Antipolis, July 2005, supervisor : P. Rives.
  - M. Fruchard, « Méthodologies pour la commande de manipulateurs mobiles non-holonomes », École des Mines de Paris, September 2005, supervisors : C. Samson, P. Morin.
- *Current Ph.D. Students* :
  - S. Benhimane, « Vers une approche unifiée pour le suivi temps-réel et l'asservissement visuel », supervisors : E. Malis, P. Rives.
  - M. Maya Mendez, « Commande référencée capteur des robots non-holonômes », École des Mines de Paris, supervisors : C. Samson, P. Morin.
  - C. Mei, « Cartographie et navigation autonome dans un environnement dynamique », École des Mines de Paris, supervisor : P. Rives.
  - G. Silveira, « Application de l'asservissement visuel au contrôle d'un drone aérien », École des Mines de Paris, supervisors : P. Rives, E. Malis.
  - V. Brandou,« Stéréo locale et reconstruction 3D/4D », université de Nice-Sophia Antipolis, supervisors : E. Malis, P. Rives.
- *Current Postdoc Students* :
  - Andrew Comport, « Vision-based Navigation in Urban environments »,MobiVIP Project, supervisors : P. Rives, E. Malis.
- *Participation in Ph.D. and H.D.R committees* :
  - C. Samson has participated in two Phd defense jurys.
  - P. Rives has participated in four Phd (one in Girona (Spain)) defense jurys and one HDR committee.
  - P. Morin has participated in one Phd defense jury.
- *Training periods* :
  - M. Vargas, « Robust visual servoing », 6 months, supervisor : E. Malis.

9.6. Teaching

- Lecture courses at the "6th Summer School on Image and Robotics" (University of Guanajuato, Mexico) *Visual servoing* (E. Malis, 4 hours).
- Internet lecture courses at the first International Online Course on Visual Servoing Techniques (E. Malis).

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