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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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 testbed for outdoor experiments is constituted by two electrically powered car-like vehicles called CyCab. 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, Mauro Maya Mendez, Minh-Duc Hua.

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 [62]. 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* [61], used to solve trajectory planning problems, and *time-varying feedback control* techniques [50], 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 [12] which is a general framework for addressing sensor-based control problems. As for our studies about mobile robot control [13], 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* [56] for "highly" nonlinear systems.

3.3. Active perception

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

Participants: Ezio Malis, Patrick Rives, Vincent Brandou, Christopher Mei, Alessandro Corrêa-Victorino, Geraldo Silveira, Andrew Comport, Omar Tahri, Adan Salazar, Hicham Hadj-Abdelkader, Youssef Rouchdy.

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 [49], [59]. In the ICARE project, we work for example on the calibration problem of omnidirectional cameras [31].
- *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. One of the problems that we study in the ICARE project is the fusion of sensory data associated with an omnidirectional central catadioptric camera and a laser range finder [31].

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 [25].
- *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* [60] whose stability is independent of the noise distribution. In the ICARE project, we have successfully applied this kind of technique to the robot motion estimation problem when using a laser range finder [15].

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 [11]. 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 [12] 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, Christopher Mei, Geraldo Silveira, Andrew Comport, Cyril Joly, Gabriela Gallegos.

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 [52]. 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 [46].

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 [15], [16].

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 [11]. 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. This formalism is generic enough to suggest that it 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*
  The experimental platform at INRIA Sophia-Antipolis is based on two instrumented electrical cars of the *CyCab* family and destined to validate researchs in outdoor robotics and, more precisely, in the domain of *vehicles for the future*. *CyCabs* are 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.

4.2. Intelligent Transport System

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

Participants: Patrick Rives, Ezio Malis, Cyril Joly, Andrew Comport, Youssef Rouchdy.

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).

Our activity concern the domain of future transportation systems, with a participation in the national Predit Project MOBIVIP. In this project, we address autonomous and semi-autonomous navigation (assistance to driving) of city cars by using information data provided by visual or telemetric sensors. This is closely related to the problems of localization in an urban environment, path planning and following, subjected to stringent safety constraints (detection of pedestrians and obstacles) in large and evolutive structured environments.

We are also involved in the ANR-PREDIT LOVE with Renault and Valeo as industrial partners. Associated with the *Pôle de compétitivité System@atic*, this project aims at preventing pre-crash accidents by real-time vision-based detection and tracking of pedestrians and dynamic obstacles.

4.3. Indoor Robotics

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

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

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: Claude Samson, Patrick Rives, Ezio Malis, Pascal Morin, Minh-Duc Hua, Samuel Bueno [CenPRA de Campinas (Brazil)], Geraldo Silveira [CenPRA of Campinas (Brazil) from 11/01/04 PhD student], José Raul Azinheira [IST of Lisboa (Portugal)], Tarek Hamel [Univ. of Nice-Sophia Antipolis].

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 (see Figure 1). 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).

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 GRICES. 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

Figure 1. Blimp AS800 of the CenPRA Laboratory (Campinas, Brazil)

adapted to this type of application. They have been tested in simulation and are currently being validated on the devices developed by our partners. The know-how resulting from the AURORA project, is going to be valorized in the FP6 STReP European Project PEGASE led by Dassault, which aims at developing embarked systems for autonomous take-off and landing when dedicated airport equipments are not available. In this project, we are in charge, jointly with the INRIA/LAGADIC and the IST/DEM project-teams, of developing visual-servoing solutions adapted to the flight dynamic constraints of planes and helicopters.

While the AURORA project is primarily dedicated to blimps, we have also initiated this year a new collaboration on the control of another type of VTOL (vertical take-off and landing), the so-called "HoverEye", developed by the french company Bertin Technologies. This small ducted fan aerial vehicle, which has the capacity to perform stationnary flight, is well suited to surveillance operations in cluttered environments. In addition, the fan's protection provided by the duct makes this type of system more robust to collisions and less dangerous for human manipulation than classical helicopters. As a counterpart, the duct is the source of complex aerodynamic effects difficult to model. In particular, the stabilization of the vehicle in the presence of wind is an important issue for this type of system. SCUAV (*Sensory Control of Unmanned Aerial Vehicles*), sponsored by the ANR and leaded by Professor T. Hamel from the University of Nice-Sophia Antipolis, is a new project devoted to the control of this system. The objective of our participation in this project is to propose feedback control strategies in order to improve the stability of this type of VTOL, especially in the presence of wind, for both stationnary and cruising flight.

5. Software

5.1. Software

Participants: Ezio Malis, Benoit Vertut.

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. Benoit Vertut, is in charge of developing a real time library implementing the ESM functionalities.

The OMNIDIRECTIONAL CALIBRATION TOOLBOX is a software developed for the calibration of different types of single viewpoint omnidirectional sensors (parabolic, catadioptric, dioptric), based on a new calibration approach that we have proposed in [30]. The toolbox is freely available over the Internet [1].

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, Mauro Maya Mendez, Minh-Duc Hua, Tarek Hamel [Univ. of Nice-Sophia Antipolis].

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 [7], [8], [9], 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 critical underactuated mechanical systems

We have pursued our extension, initiated last year, of the transverse function approach to underactuated mechanical systems. We consider mechanical systems which are kinematically invariant on a Lie group G (like e.g. $G = SE(3)$ or any of its sub-groups) and submitted to body-fixed control forces and torques. This corresponds to the classical framework of the so-called "Euler-Poincaré" equations [55]. This class of systems contains most known underactuated devices (underactuated manipulators, hovercrafts, VTOLs, blimps, satellites subjected to actuation failure, etc). In the absence of external forces (gravity, wind), these underactuated systems are critical in the sense that they are locally controllable at zero velocity while their corresponding linear approximation is not. While the stabilization approach evoked in this section applies to both the critical and non-critical case, it is more specifically dedicated to the former case for which classical (linear-like) feedback design approaches fail. As for nonholonomic systems [8] (another class of critical systems) the objective is to derive feedback laws that ensure practical stabilization of *any* (not necessarily feasible) smooth reference trajectory in the configuration space. In addition, the velocities and control inputs should remain bounded and, preferably, converge to zero when $g_r(t)$ converges to a fixed configuration. These constraints, which are important for applications, render the extension of the control design developed in [8] particularly difficult.

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

The control design that we had proposed last year [57] to address this stabilization problem was limited to a specific class of systems evolving on three dimensional Lie groups (typically $\mathbb{R}^3$, $SE(2)$ and $SO(3)$). The results that we have obtained this year extend this approach in two directions. First, the control design can now be performed for any STLC (i.e. Small Time Locally Controllable) defined on a three dimensional Lie groups. For example, contrary to the result reported in [57], it applies to (STLC) underactuated spacecrafts with two control torques not aligned with the principal inertia axes. Second, the control design is no longer limited to three dimensionnal Lie groups and systems underactuated by only one control. For example, we have shown that our method applies to the challenging case of a spatial rigid body (i.e. $G = SE(3)$) with one force and two torques (i.e. a system underactuated by three controls). Also, for a specific choice of the control parameters, we have provided a proof of convergence of the velocities and control inputs to zero, for second-order chained systems, when the reference trajectory is reduced to a fixed point. The analysis of this convergence issue for more general systems (i.e. on more general Lie groups) is still a pending question. These results have been collected in a research report [38] and presented at an international conference [32].

6.1.2. Control of a P-VTOL vehicle

In order to get familiarized with the problem of controlling underactuated aerial vehicles subjected to gravity and capable of Vertical Take-Off and Landing (VTOL), we have re-visited the planar case (PVTOL) corresponding to displacements restricted to the vertical plane. The existing bibliography on the subject has allowed us to get acquainted with the major control methods proposed so far (model linearization and linear control design, feedback linearization in relation with differential flatness properties, Lyapunov control design, etc.). The well-documented PhD-thesis [58] of J.-M. Pflimlin (co-supervised by T. Hamel) on the modeling and control of a VTOL prototype experimented by Bertin Inc. has also been an important source of information, concerning the measurement and modeling of drag forces exerted on the vehicle in particular. This study concretized in working out an initial version of a "realistic" dynamical model which takes the effects of wind variations and gusts into account and can be used for simulation purposes in order to test the robustness of various control strategies and schemes. Two nonlinear feedback control laws have also been derived, both aiming at the stabilization of the position of the vehicle's center of mass either at a fixed point or along a pre-specified reference trajectory. The first one, obtained by applying a "conventional" Lyapunov design to a slightly simplified model, has the particularity of using explicitly the passivity of drag forces and the specificity of drag momentum forces associated with the use of a ducted fan. It yields semi-global exponential stabilization of a fixed desired position in the absence of wind, and its robustness against crosswind has been validated in simulation. The less conventional second control law has been derived with the Transverse Function approach in order to "practically" stabilize any reference trajectory (within the bounds imposed by the physical system). With respect to classical control methods, this approach presents the advantage of remaining applicable when the vehicle's orientation along the reference trajectory is not known (a major difficulty when trying to apply linear control techniques based on approximate linearization, since this orientation depends on poorly known drag forces), or even when the linear approximation of the vehicle's equations along the reference trajectory is not controllable. Nevertheless, a "desired" orientation still has to be specified, in relation to the fact that the approach aims at stabilizing the complete state of the system. The fixed orientation associated with a motionless vehicle in the absence of wind is the simplest (and a fairly natural) possibility that we have tested in the first place. However, it is likely that better choices, in the sense of enlarging the set of reference trajectories which can be stabilized without making "maneuvers" (without thrust inversion, in particular), can be made. This is one of the issues that we plan to study in the continuation of this work whose main results are detailed in the Master thesis of M.-D. Hua [39].

6.1.3. Unified control design for underactuated ground, marine, and aerial vehicles

From a general perspective, many underactuated ground, marine, and aerial vehicles share, in the first approximation, a common basic structure consisting of a single main body to which a thrust force is applied for longitudinal propulsion and whose orientation is fully steerable (in nominal conditions) by various complementary means of actuation (rudders, ailerons, elevators, moment gyros, lateral propellers or gas jets, etc.). For instance, hovercrafts, ships, submarines, aeroplanes, blimps, rockets and missiles, helicopters and VTOL vehicles belong to this category. They are also immersed in an ambient fluid (water or air, usually)

–with the exception of vacuum in space— which exerts reaction forces on them in the form of drag and lift. These latter forces, whose knowledge and/or measurement is always imprecise to some extent, largely shape and determine the domain of operation of each vehicle. Some of these vehicles move on a plane surface (like ships on rivers or oceans, and hovercrafts either on ground or on water), whereas others are meant to evolve in the 3-dimensional space (planes, submarines, helicopters, rockets). Concerning the mathematics of these systems, passing from the planar case to the spatial case corresponds to a classical "lifting" operation between the 3-dimensional Lie group $SE(2)$ (planar case) and the 6-dimensional Lie group $SE(3)$ (spatial case). This does not pose fundamental difficulties. From the control viewpoint, all these systems would share the same controllability properties (local controllability at zero velocity, for instance) if their actuators could produce instantaneous forces with unlimited positive and negative amplitude. In this case it would be theoretically possible to "practically" stabilize almost any desired (reference) trajectory, either in $SE(2)$ or in $SE(3)$, with arbitrary tracking precision. In practice, actuators limitations, the nature of which depends much on the vehicle's type and specifications, significantly reduce the control possibilities. This issue is much related to the notion of "nominal" operational conditions which basically falls down to characterizing, in relation to environmental conditions, the properties of trajectories in the configuration space which can be locally stabilized. Another common feature of this class of vehicles, also shared by nonholonomic vehicles –like cars–, is the existence of solutions to the system's dynamics (which may be seen as potential reference trajectories or dynamical equilibria) which cannot be (locally) stabilized by "classical" linear or nonlinear control techniques because the linear approximation of the system's dynamics about these equilibria is not controllable (nor even stabilizable), eventhough the original system remains locally controllable at these equilibria. These particular equilibria do not form a dense set (i.e. they are isolated) so that it is tempting to just ignore them in the process of designing control solutions. However, in some cases such a singular equilibrium belongs to the nominal domain of operation of the vehicle. Ignoring it then inevitably results in incomplete control solutions. A good illustration of this are restpoints for a ship, a hovercraft, or a blimp in the absence of sea current or crosswind. It is well known that no classical control solution can asymptotically stabilize these equilibria. Addressing this problem in the case of nonholonomic vehicles has, in the past, motivated numerous control studies, with temptative extensions to the underactuated case by a few authors. This issue is closely related, as one can guess intuitively, to the possibility of producing effective maneuvers via feedback. Note also that restpoints do not constitute singular equilibria for other underactuated vehicles, like helicopters and VTOL vehicles. This is due to the action of the gravity field which renders the linearized dynamics of these systems at restpoints controllable (provided, of course, that the longitudinal thrust actuator can produce a lift force larger than the vehicle's weight). The aforementioned controllability and feedback stabilization issues, some of which have not yet been entirely elucidated despite important progress made in this area of nonlinear control theory, tend to blur the picture of structural unity advocated previously. This in turn contributes to explain –as a complement to the long and continuing history of development of man-made underactuated machines and the progressive introduction of automated control– why no general control design framework for these systems has –to our knowledge– been formulated before. The increasing involvement of ICARE in the control study of underactuated mechanisms finds a natural extension in such an endeavor. In doing so, we are quite aware of the enormous amount of research and development devoted in the past, at the academical level and in numerous industrial laboratories, to the design of autopilots for aeroplanes, ships, helicopters and, more recently, robotized drones, VTOL vehicles, and similar systems. Our ambition is certainly not to provide on-the-shelf control solutions competing with well established existing industrial solutions, such as those developed in the aeronautical and aerospace industries for decades. This would be preposterous and unrealistic. Nevertheless, we believe that working on a general control design framework based on recent advances in nonlinear control theory can be profitable i) to complement the comprehension of existing designs, ii) to the education of control engineers, and iii) to the development of control solutions for the next generation of underactuated robotic vehicles. This is a long term research theme which is based on and encompasses all control studies that we are conducting on specific underactuated vehicles (blimps, VTOLs, etc).

6.1.4. Sensor-based control of non-holonomic mobile robots

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 of the environment are inaccurate, so that the estimation 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.

A traditional approach consists in calculating an estimate of the robot's posture which is used in a feedback law derived in cartesian coordinates. Such an estimate can be obtained, for example, from the knowledge of the signal function Jacobian at the desired operating point and the sensor output. This approach has been investigated last year, and we have provided sufficient conditions on the robot's posture estimation error under which the practical stabilization of arbitrary reference trajectories, based on the control approach [8], can be guaranteed. This result has been presented this year at an international conference [26].

Another approach, initially developed for manipulator arms, consists in directly using the sensory measurements in feedback laws derived in signal coordinates (i.e. in a system of coordinates associated with the sensory output function). Compared to the previous approach, an advantage of this method is to bypass the reconstruction step of the robot's posture which may require a significant amount of information on the robot/environment and/or lead to noise amplification. To apply this method, one must first design controllers in signal coordinates. We have shown that the control laws proposed in [8] can also be expressed in such coordinates. To this purpose, the sensory output function must be known, as well as its inverse and derivative. However, approximations of these functions are sufficient to locally ensure a practical stabilization. Different possibilities for these approximations have been proposed and tested in simulation. While these different choices do not yield much different results quantitatively (i.e. the resulting tracking precision is similar), qualitative differences in term of the tracking error dynamics have been observed. Comparisons with the control laws derived in cartesian coordinates (i.e. based on an estimation of the robot's posture) do not, however, indicate a clear advantage of one approach over the other. All these results have been collected in a research report [37].

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, Vincent Brandou, Geraldo Silveira, Omar Tahri.

The achievement of complex robotic applications such as autonomous exploration of large scale environments, observation and surveillance by aerial robots, or medical robotics requires to develop and combine methods in various research domains: sensor modeling, active perception, visual tracking and servoing, etc. This raises several issues.

- To simplify the setup, it is preferable to integrate, as far as possible, methods 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 sensors 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 [64] approaches have also been studied. In 2005, we had developped a grid-based approach using the unified projection model from Geyer and Barreto [42] [51]. In 2006, we have continued our work on omnidirectional calibration [30], and improved our freely available calibration toolbox[2], to enable the calibration of a larger range of omnidirectional cameras.

6.2.1.2. Coupling omnidirectional central catadioptric cameras and laser range finder :

We have studied the problem of finding the relative position between an omnidirectional camera and a laser range finder in view of the fusion of sensory data [31]. Two distinct cases have been analysed: the case where the laser beam is visible in the omnidirectional image and the case where it is invisible (close infrared). In the first case, we have considered not only the association between 3D laser points and points in the image, but also the association between 3D lines extracted in the laser range scan and line images. In the second case, we have shown that associating edges in the image with edges in the laser is not sufficient to calibrate the sensor. For this situation, we have adapted the work from [67] to omnidirectional sensors. Figure 2 illustrates the calibration results by re-projecting a laser scan in an omnidirectional image.

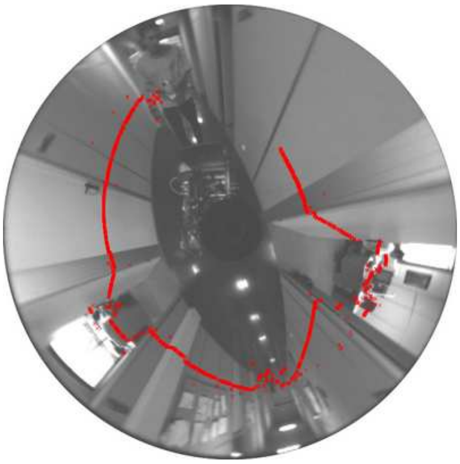

Figure 2. Laser data superimposed on an omnidirectional image

6.2.1.3. Low level image processing for central catadioptric cameras :

As mentioned above, the use of omnidirectional cameras enhances the field of view. However, the images obtained with this type of sensor suffer generally from significant deformations. This makes the classical operators (i.e. filtering operators in general) used in the perspective projection case not very suitable to the omnidirectional case. Our objective is to develop a new formulation of these operators better adapted to catadioptric sensors. There exist several ways to address the problem of image deformations in catadioptric sensors. In the calibrated case, it is possible to remove the distortion and work on a local perspective plane. This can be performed efficiently when a limited image zone is concerned. For instance to match Harris point between two images, we first compute the projections of the detected points' neighborhoods on local

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

perspective planes, and then we compute correlations between these planes to make the matching. The experimental results that we have obtained confirm the superiority of this method over more classical ones (based e.g. on correlations computed on the catadioptric plane). Similarly, the image's intensity gradient can be defined in the local perspective plane associated with any given point. More precisely, one has:

$$\begin{aligned}\frac{\partial I}{\partial xp} &= \frac{\partial I}{\partial xc}\frac{\partial xc}{\partial xp} + \frac{\partial I}{\partial yc}\frac{\partial yc}{\partial xp}\\ \frac{\partial I}{\partial yp} &= \frac{\partial I}{\partial xc}\frac{\partial xc}{\partial yp} + \frac{\partial I}{\partial yc}\frac{\partial yc}{\partial yp}\end{aligned}$$

with $\frac{\partial I}{\partial xp}$ and $\frac{\partial I}{\partial yp}$ the gradient's coordinates expressed in the local perspective plane's coordinates, $\frac{\partial I}{\partial xc}$ and $\frac{\partial I}{\partial yc}$ the gradient's coordinates expressed in the catadioptric plane's coordinates, and $\frac{\partial xc}{\partial xp}, \frac{\partial xc}{\partial yp}, \frac{\partial yc}{\partial xp}, \frac{\partial yc}{\partial yp}$ the jacobian of the coordinate transformation between the catadioptric plane and the local perspective plane. This jacobian only depends on the camera geometry, so that it can be pre-computed.

When the whole image needs to be processed, the above approach (local by nature) will be computationally very expensive. For example, for the problem of matching points of interest (like, e.g., Harris points), the calculation of many local perspective planes introduces a lot of redondant information. Also, whatever the considered local plane, it is impossible to encompass the full field of view without important deformations in the image border. Another way to address the deformation problem is to define the operators in another space where the signal is less deformed, and compute them on the image catadioptric plane. For instance, the convolution between two images and the optical flow can be defined on the sphere. The image filtering can also be done after warping the original image to a projection on the sphere. This can be achieved using spherical harmonics theory.

6.2.2. Robust real-time visual tracking and servoing

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. 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 [3]. 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 [3] 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-based methods relying on the direct use of the grey level data without assuming any geometrical structure on the images seem more appropriate.

In [53], we have shown that a more general system can be obtained by integrating template-based visual tracking algorithms [45] and model-free vision-based control techniques [3]. 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. We have pursued the unification within a single framework of the ESM visual tracking method and model-free visual servoing techniques.

Firstly, we have extended to all single viewpoint sensors not only the ESM visual tracking [28], but also a homography-based visual servoing scheme [21], [22] that uses directly the output of the ESM. Single viewpoint sensors include omnidirectional cameras that are particularly useful for several robotic applications such as motion estimation and site recognition. The ESM visual tracking algorithm has been successfully applied to the precise six degrees of freedom motion estimation of a mobile robot from the data provided by an omnidirectional camera [27]. Figure 4 shows the comparison between the odometry considered as ground truth (solid line) and the values obtained from the tracking of the templates of Figure 3, using a robust approach to remove specularities and occlusions (line with symbols: the values are nearly superimposed with the solid lines indicating the odometry). The number of iterations is indicated on the right axis in figure 4.

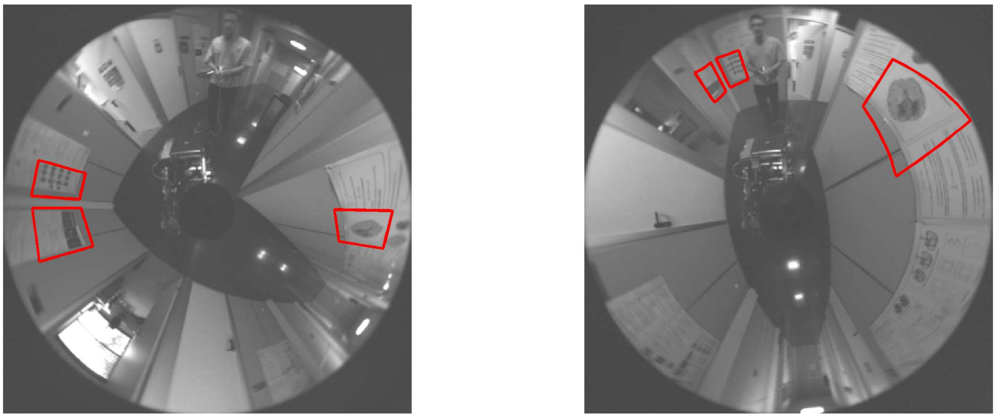

Figure 3. Left: first image of a tracking sequence. Right: Image 120 of a tracking sequence.

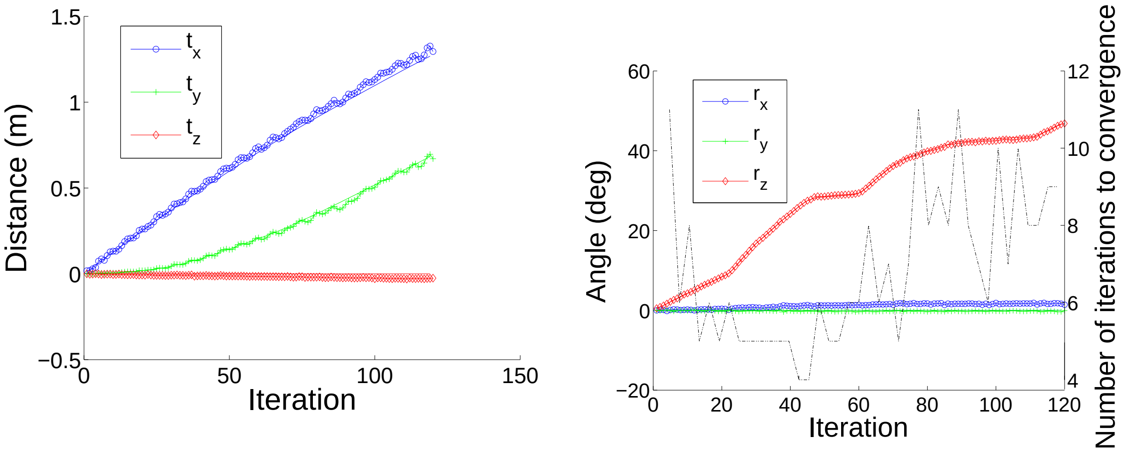

Figure 4. Left: Translation estimate. Right: Rotation estimate. The odometry was used as ground truth.

Another step in the integration of template-based visual tracking algorithms and model-free vision-based control techniques has been achieved in [35]. Indeed, we have proposed a new visual servoing technique for which neither the goal (desired) image nor a metric model of the scene are available in advance. In this case, the task objective is defined solely in terms of (possibly distant) Cartesian pose(s) to be attained. The current pose is obtained as a "visual odometry". In order to improve the accuracy, stability, and rate of convergence of the vision-based estimations, the unknown scene is represented as a collection of planar regions [65]. The proposed visual servoing then relies on two key techniques. Firstly, it is based on a Planar Region Detector (that we have proposed in [34]), so that the known planes may leave the field-of-view. It is important to remark that complex strategies to deal with the visibility constraints are thus not required with our approach (see Figure 5 for an example). Secondly, the ESM visual tracking technique is also used to estimate the piecewise planar structure of the scene on-line. This approach is suited to various real-time applications such as the visual SLAM problem and vision-based navigation tasks in unknown, large-scale environments.

A piecewise planar approximation of the 3D structure may be not appropriate for some applications. For this reason, we have started to investigate how to extend the ESM visual tracking to generic 3D objects [40]. Even if real-time performances have not be achieved yet, preliminary results obtained with Matlab show that it is possible to estimate on-line a parametric model of a 3D smooth surface.

Figure 5. Left: A plane is initialized in the first image. Center and right: the desired poses, the performed trajectory, and the 3D reconstructed scene with the exploited planes and after performing a region growing.

6.2.3. Active sensor-based control

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

This joint collaboration with IFREMER aims at developing, implementing and testing an original robotic method to compute the 3D metric reconstruction in order to describe and quantify the biodiversity in deep-sea fragmented habitats. The images used for the reconstruction are acquired from an underwater vehicle lying on the seafloor. A stereo rig 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 to constrain the image acquisition process thanks to a visual servoing approach in order to reduce the number of unknown parameters in the reconstruction computation. It consists in capturing a reference image with the right camera at a given position, and then converging towards this position with the left camera. The distance and the angle between the two cameras constrain the trajectory followed by the cameras by iterating the visual servoing (see figure 6-left). Because the underwater cameras are not the same, and the intrinsic parameters may vary according to the environment, we have focused our attention on an intrinsic-free visual servoing method [5]. The proposed visual servoing scheme has been validated experimentally on two different robots: the robot ANIS at INRIA and the robot *MAESTRO* at IFREMER [24]. After the validation of our technique in laboratory experiments, in-pool trials have been carried out to finalize the development of the overall technique and to prepare for the extensive sea trials. During the Momareto cruise in 2006 in the Azores, we have tested the method on the Ifremer's Remotely Operated Vehicle (ROV) *Victor6000*, with the stereovision rig hung from the tip of the robotic arm *MAESTRO* (see figure 6-right). Underwater images were acquired by the stereo rig on two different sites (Menez Gwen and Lucky Strike) deep down to 1700 meters.

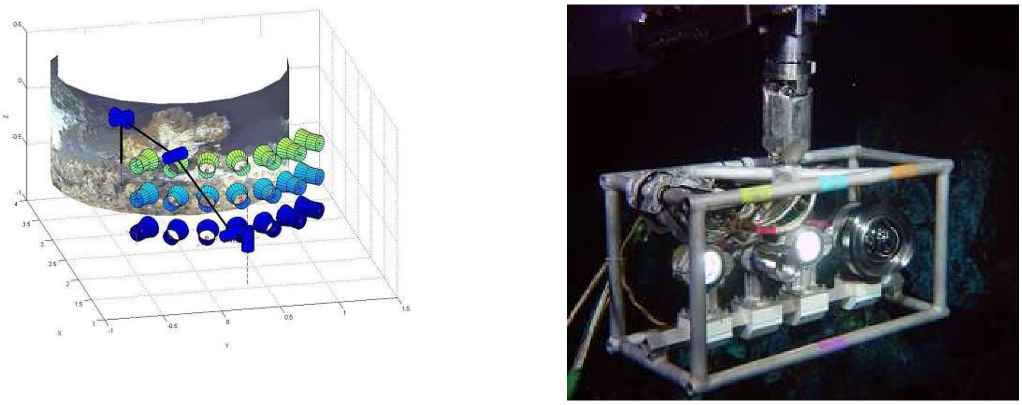

Figure 6. Left: Trajectories performed by the MAESTRO arm, Right: Stereo rig IRIS

6.3. Robot navigation and guidance

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

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

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

- Localization, navigation and map building in both indoors and outdoors environments. We are interested in developing robust approaches allowing for the safe navigation of a robot in unknown and large environments. A central issue concerns the use of local measurements acquired by the robot during the exploration for the building of unbiased and consistent global maps.
- Automatic guidance for mobile robots. We address the problem of guiding a mobile robot with respect to features extracted from the environment.

6.3.1. SLAM in indoors environments

Although it has been intensively studied for two decades, the SLAM (*Simultaneous Localization And Mapping*) problem remains largely open. Our past contributions on the subject are summarized in previous activity reports, and in [15], [16]. 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. Our framework has been successfully validated on our experimental mobile robot ANIS.

6.3.1.1. Drift compensation

The indoor mobile robot that we consider is equipped with a laser scanning device which produces a planar cross section of the environment. The sensor-based navigation 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. 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.
Following the hybrid geometrical/topological representation presented last year, we define the global map as a set of geometric *places* (where the robot is localized with metric precision) connected by a global topological model (for which the localization is performed in a semantical way). However, the lack of a precise metric between the different places introduces *inconsistencies* in the global model when the robot returns to a place previously explored. This is often referred to as the loop closing problem in the SLAM approach. To address this issue, we had proposed last year [66] 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*. This year, we have improved this method by taking into account the cross correspondences in the formulation of the local constraints and considering a probabilistic model of uncertainties in the optimization process [36].

The method has been validated on the robot ANIS which has successfully explored and mapped a floor of our laboratory in a fully autonomous mode. In this experiment, the robot has covered a distance of about hundred meters, closed one loop, and built five places connected by a graph of accessibility. A partial reconstruction of the environment resulting from this experiment is represented on Figure 7, where we can observe the five places detected, each of which is endowed with a local reference frame localized in the global map by its pose and an uncertainty ellipsoid. The places are connected by a topological structure not represented on this figure.

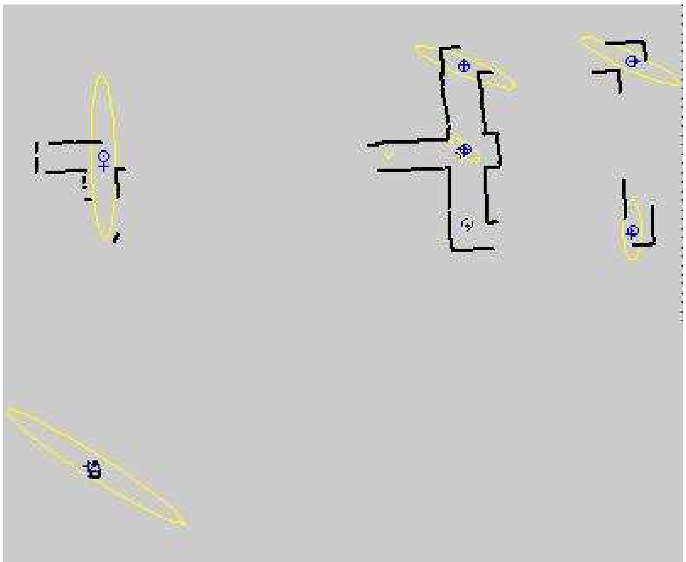

Figure 7. Exploration, localization, and mapping of a large indoor environment

6.3.1.2. Combining laser and vision for simultaneous localisation and mapping (SLAM)

Much progress has been made recently, in the SLAM community, on the application of filtering methods to the map building of large-scale environments. However, sensors limitations still reduce the complexity of the environments that can be processed. We attempt to address some of the issues in map building and motion estimation by a novel combination of sensors: an omnidirectional camera and a 2D laser range finder. In particular, the problems of reliable data association, observability and loop closing are simplified by adding visual information. Figure 8 illustrates a detected loop closure situation. Figure 9 shows how vision can help to constrain the translation in a corridor-like environment.

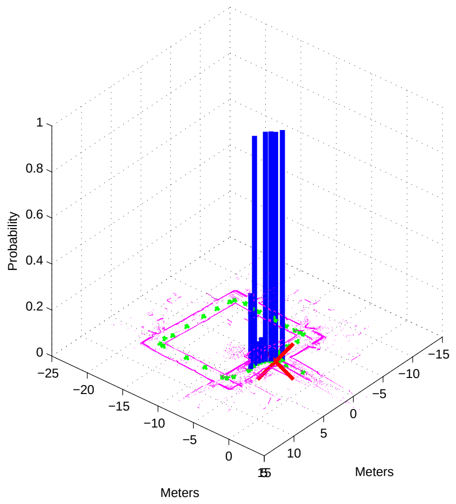

Figure 8. Loop closure detection with panoramic vision

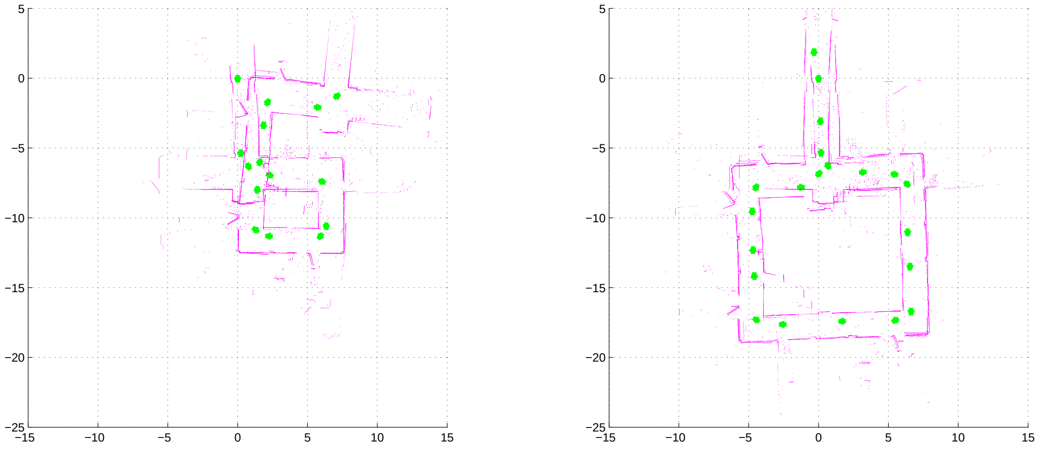

Figure 9. Motion estimation using: scan matching (left), scan matching combined with vision (right)

6.3.1.3. Structure from motion from lines for central catadioptric cameras

Points or planes are not always available for motion estimation in man-made environments. This observation has motivated the development of methods for line image extraction, estimation and tracking in omnidirectional images. Our work on this topic has been published in [29] where we also describe a minimal parametrisation with Lie algebras for structure and motion from lines based on the work from Bartoli and Sturm [43], [44].

6.3.2. Visual navigation for a mobile robot in urban-like environments

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. The objective of this work is to design and develop a stereo vision system for urban vehicles, so that they can achieve (semi)autonomous missions. This work is part of the national project Mobivip, aimed at autonomous vehicle navigation in urban environments, which began in 2003. Prior work on this subject has been published in which a planar model-based method is used for detecting and tracking the road plane, and in [63] where it is further assumed that the remainder of the urban environment can be approximated by piecewise planar structures.

These works have been reviewed in detail and the principal objective has been decomposed into two subproblems. Firstly, the scene is reconstructed off-line from the training sequence. This reconstruction phase involves recovering both a structural model of the environment and the trajectory of the training camera with respect to some world coordinate system. This stage has less computational constraints than the second stage and both future and past information is available. Secondly, the Cycab is controlled on-line towards its objective using visual information. At this point the vehicle's initial position can be initialized with respect to the a-priori 3D model of the environment and real-time and robust real-time model-based techniques can be used to track the current position of the vehicle. The aim here is to perform the mission while remaining robust to uncertainties in the environment such as changes in illumination, shadows, occlusions, etc..

Thus far, a novel approach to 3D visual odometry has been proposed which avoids explicit reconstruction of the structure in the scene. An appearance based tracking method has been developed using image transfer of the quadri-focal tensors [41]. In this way the stereo relationship between positions in a sequence may be obtained which describes the trajectory of the cameras in projective space. If the stereo pair is calibrated then the only unknown is the pose between two pairs of images, and it is possible to develop an accurate non-linear iterative minimization procedure [48], [45] to track the multi-focal tensor across the sequence. The advantages of this approach are multiple. First, it is a 3D model-free approach that only requires dense 2D correspondences between the stereo image pair. Then, no initialization is required between a 3D model and the camera since the tracking is performed relative to the camera position. Also, only one single global estimation process is necessary, therefore eliminating sources of error and allowing for robust statistics to be used [47]. Finally, the use of second order minimisation techniques [54] provides fast convergence rates. This type of technique can also be used on-line in real-time with little modification. If the cameras used for the reconstruction are different from those used for the vehicle, or if the calibration parameters have changed, then it is possible to work in projective space. Figure 10 shows two examples of the reconstructed trajectories of a car moving in Versailles, France. The trajectories are superposed to a bird-eye view of the city taken from GoogleEarth.

7. Contracts and Grants with Industry

7.1. Project MiniROC (ECA/DGA)

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

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

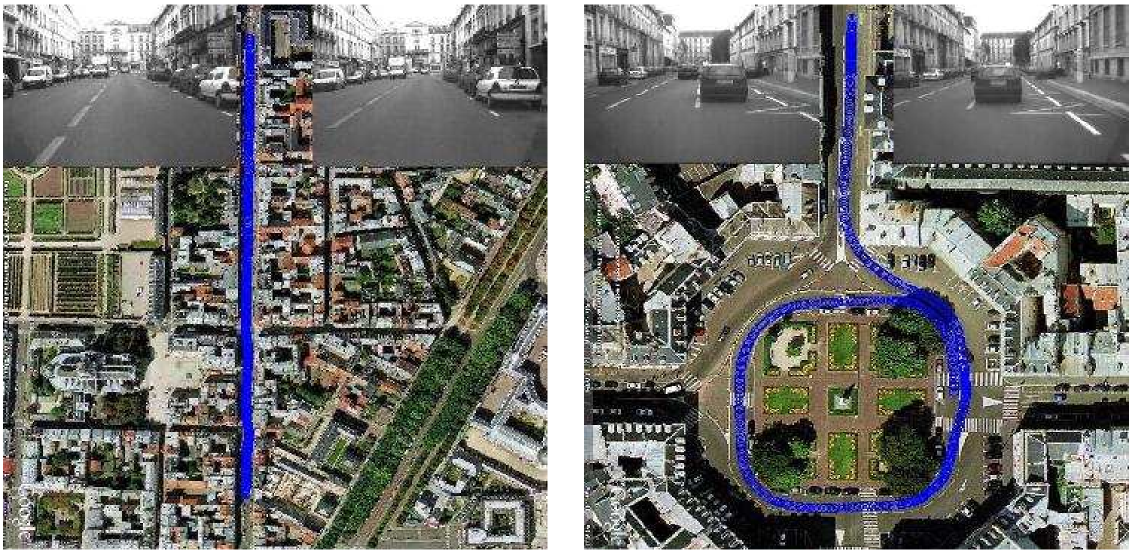

Figure 10. Left: straight line trajectory. Right: round-about trajectory.

This project concerns the on-line indoor 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.

7.2. Project Themis (Ifremer)

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

Participants: Ezio Malis, Patrick Rives, Vincent Brandou.

The objective is to design an active stereovision head controlled via visual servoing techniques (see Section 6.2.3.1). An industrial device was designed and first trials have been done in august 2006 on the Lucky Strike site (depth: 1700m) in the Azores. 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. Project MobiVIP (Predit3)

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

Participants: Patrick Rives, Ezio Malis, Andrew Comport, Cyril Joly.

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).

8.2. National Activities

Participants: Patrick Rives, Ezio Malis, Christopher Mei, Omar Tahri, Hicham Hadj-Abdelkader, Youssef Rouchdy.

8.2.1. ANR-Predit: LOVe

Associated with the *Pôle de compétitivité System@atic*, this project aims at preventing pre-crash accidents by real-time vision-based detection and tracking of pedestrians and dynamic obstacles. Our partners are INRIA/E-MOTION, INRIA/IMARA, INRETS/LIVIC, CEA/LIST, CNRS/IEF, CNRS/Heudiasyc, CNRS/LASMEA, ENSMP/CAOR, Renault, Valéo.

8.2.2. ANR Caviar (CAtadioptric VIsion for Aerial Robots)

This project aims at studying the contribution of omnidirectional vision in aerial robotics. With a SLAM-like approach, we propose to develop methods and algorithms based on catadioptric omnidirectional vision in order to perform the mapping and 3D-modeling of an urban surrounding. Our partners are CNRS/CREA (Université de Picardie Jules Verne), CNRS/LAAS, CNRS/Le2i (Université de Bourgogne), INRIA/PERCEPTION.

8.3. FP6 STReP European Project Pegase

Participants: Patrick Rives, Ezio Malis.

This project, led by Dassault, aims at developing embarked systems for autonomous take-off and landing when dedicated airport equipments are not available. We are in charge, conjointly with the INRIA/LAGADIC and the IST/DEM project-teams, of developing visual-servoing solutions adapted to the flight dynamic constraints of planes. Our partners are Dassault, EADS, ALENIA, EUROCOPTER, IJS, INRIA/LAGADIC, INRIA/VISTA, CNRS/I3S, IST/DEM (Portugal), Università di Parma (Italy), EPFL (Swiss), ETHZ (Swiss), Institut "Jozef Stefan" (Slovenie).

8.4. Joint research program INRIA/FAPESP

Participants: Patrick Rives, Ezio Malis, Geraldo Silveira.

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 GRICES. 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).
- P. Rives has been a member of the Program Commitee of the following conferences: RFIA 2006, IEEE-ICRA 2006, IEEE-ICRA 2007, JNRR 2007.
- E. Malis has been a member of the Program Commitee of the following conferences: IROS 2006, ICARCV 2006, VISAPP 2006, CVPR 2006, ECCV 2006.

9.2. International conferences

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

- IEEE International Conference on Robotics and Automation (ICRA), Orlando, USA, May 2006,
- British Machine Vision Conference (BMVC), Edimburgh, Scotland, September 2006,
- IEEE/RSJ International Conference on Intelligent Robots Systems (IROS), Beijing, China, October 2006,
- IEEE Conference on Decision and Control, San Diego, USA, December 2006.

9.3. National conferences

Icare's researchers have presented their work at the following conference:

- Reconnaissance des Formes et intelligence Artificielle (RFIA), Tours, france, Janvier 2006.

9.4. Activities of general interest

- C. Samson is a member of the "Bureau du Comité des Projets" 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*.
- 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* :

- *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.-D. Hua, « Commande de systèmes mécaniques sous-actionnés », université de Nice-Sophia Antipolis, supervisors : P. Morin, T. Hamel.
    - 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.
    - G. Gallegos, « Exploration et navigation autonome dans un environnement inconnu », École des Mines de Paris, supervisor : P. Rives.
    - C. Joly, « Conditionnement des méthodes de VSLAM en environnement extérieur », École des Mines de Paris, supervisor : P. Rives.
    - A. Salazar, « SLAM en environnement extérieur dynamique », École des Mines de Paris, supervisor : E. Malis.
- *Current Postdoc Students* :
    - Andrew Comport, « Vision-based Navigation in Urban environments », MobiVIP Project, supervisors : P. Rives, E. Malis.
    - Omar Tahri, « Low-level image processings with catadioptric cameras », Caviar Project, supervisors : P. Rives, E. Malis.
    - Youssef Rouchdy, « Real-time visual tracking of articulated and/or deformable objects », LOVe Project, supervisor : E. Malis.
- *Participation in Ph.D. and H.D.R committees* :
    - E. Malis has participated in one Phd defense jury.
    - P. Morin has participated in one Phd defense jury.
    - P. Rives has participated in four Phd defense juries.
- *Training periods* :
    - M.-D. Hua , « Commande d'un minidrone à hélice carénée », 6 months, supervisors : C. Samson, P. Morin, T. Hamel.
    - M. Zendjebil, « Suivi en temps réel d'objets rigides avec l'algorithme ESM », 6 months, supervisor : E. Malis.

9.6. Teaching

- Course on nonlinear control in the Master EEA of the university of Nice-Sophia Antipolis (P. Morin, 25 hours Eq. TD).
- Lecture course on the control of nonholonomic and underactuated vehicles, Ecole des Mines de Paris, Options Control/Robotics (P. Morin, 3 hours).
- Lecture course on mobile robotics, Ecole Nationale des Ponts et Chaussées, (P. Rives, 3 hours).
- Lecture course on visual tracking and visual servoing, University of Sevilla, (E. Malis, 4 hours).

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