Activity Report 2011

Project-Team AROBAS

Advanced Robotics and Autonomous Systems

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Robotics

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Project-Team AROBAS

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1. Members

Research Scientists

Patrick Rives [Team leader, Senior Researcher (DR) Inria, HdR]
Claude Samson [Senior Researcher (DR) Inria, HdR]
Pascal Morin [Junior Researcher (CR) Inria, up to end of September, HdR]
Andrew Comport [Junior Researcher (CR), I3S-UNSA-CNRS, University of Nice-Sophia Antipolis, external collaborator]

Faculty Member

Tarek Hamel [Professor, I3S-UNSA-CNRS, University of Nice-Sophia Antipolis, external collaborator]

PhD Students

Alexandre Chapoulie [DGA grant]
Gabriela Gallegos [CONICYT grant, thesis defended on June 17]
Daniele Pucci [UNSA grant]
Maxime Meilland [ANR CityVIP]
Adan Salazar [CONICYT grant, thesis defended on September 6]
Glauco Scandaroli [INRIA/PACA grant]
Cyril Joly [Engineer on Contract DGA/Rapid Canari]

Post-Doctoral Fellow

Luca Marchetti [INRIA grant]

Administrative Assistant

Nathalie Woodward [Secretary (SAR) Inria, part-time]

Other

Wladyslaw Magiera [PhD student from the Institute of Computer Engineering, Control and Robotics, Wroclaw University of technology, Poland, from October 3 to December 2]

2. Overall Objectives

2.1. Introduction

The project-team activity is focused on the study of mobile robotic systems destined to accomplish complex tasks involving strong interactions with the system's environment. The underlying spectrum of research is vast due to the variety of devices amenable to automatization (ground, underwater and aerial vehicles...), of environments in which these devices are vowed to operate (structured/natural, known/unknown, static/dynamic...), and of applications for which they have been designed (assistance to handicapped people, environmental monitoring, rescue deployment after natural disasters, observation and tactical support...).

A fundamental issue in autonomous mobile robotics is to build consistent representations of the environment that can be used to trigger and execute the robot's actions. In its broadest sense, perception requires detecting, recognizing, and localizing elements of the environment, given the limited sensing and computational resources of the robot. The performance of a mobile robotic system crucially depends on its ability to process sensory data in order to achieve these objectives in real-time. Perception is a fundamental issue for both the implementation of reactive behaviors (based on feedback control loops) and the construction of the representations which are used at the task level. Among the sensory modalities, artificial vision and range finder are of particular importance and interest due to their availability and extended range of applicability. They are used for the perception and modeling of the robot's environment, and also for the control of the robot itself. Sensor-based control refers to the methods and techniques dedicated to the use of sensor data and information in automatic control loops. Its mastering is essential to the development of many (existing and future) robotic applications and a corner-stone of the research on autonomous robotics.

Most tasks performed by robots rely on the control of their displacements. Research on robot motion control largely stems from the fact that the equations relating the actuators outputs to the displacements of the robot's constitutive bodies are nonlinear. The extent of the difficulties induced by nonlinearity varies from one type of mechanism to another. Whereas the control of classical holonomic manipulator arms has been addressed very early by roboticists, and may now be considered as a well investigated issue, studies on the control of nonholonomic mobile robots are more recent. They also involve more sophisticated control techniques whose development participates in the extension of Control Theory. Another source of difficulty is underactuation, i.e. when the number of independent means of actuation is smaller than the number of degrees of freedom of the robotic mechanism. Most marine and aerial vehicles are underactuated. A particularly challenging case is when underactuation renders all classical control techniques, either linear or nonlinear, inoperative because it yields a system of linearized motion equations which, unlike the original nonlinear system, is not controllable. Such systems are sometimes called *critical*. Research in this area of automatic control is still largely open.

AROBAS genuinely tries to balance and confront theoretical developments and application-oriented challenges. 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 AROBAS –and thus maintain the coherence and unity of the project-team–, but also to understand 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 and constitute an experimental workbench for the research done in the project. In parallel, we try to develop other means of experimentation in partnership research programs. Inside Inria with other EPIs like, for example, COPRIN which develops a robotized wheeled walking aid (ANG ASSISTIVE NAVIGATION GUIDE) in the context of the Inria Large Scale Initiative PAL PERSONALLY ASSISTED LIVING. Outside Inria with others partners like for example with the IFREMER concerning underwater robotics, and with the CenPRA of Campinas (Brazil), I.S.T. of Lisboa (Portugal), and Bertin Tech. Inc. for the control of unmanned aerial vehicles (blimps and drones).

2.2. Highlights

We have demonstrated during one week in the downtown of Clermont Ferrand in real traffic conditions the performances and the robustness of the solutions of autonomous navigation and control developed in the context of the ANR project CityVIP. This experiment has been also presented in Sophia Antipolis during the open lab day organized for the European Robotics Week.

3. Scientific Foundations

3.1. Introduction

The meaning of *autonomy* in the context of mobile robotics covers a large variety of aspects, from the capabilities of moving safely and interacting with the environment, to planning, reasoning and deciding at a high level of abstraction. AROBAS *pursues a bottom-up approach with a sustained focus on autonomous navigation and the monitoring of interactions with unknown, variable, and complex environments.*

The project team is organized under the headings of two research themes : *Perception and autonomous navigation* and *Robot Modeling and Control*. Nonetheless, it matters to keep in mind that the borderline between the themes is porous since several of the associated issues and tools to address them are clearly interdependent and complementary. To highlight this interdependency, we have described in a separate section the transverse issues to the two vertical themes.

3.2. Perception and autonomous navigation

Autonomy in robotics largely relies on the capability of processing the information provided by exteroceptive sensors. Perception of the surrounding environment 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 informations 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 navigation 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.

3.2.1. Advanced perception for robotics

A key point is to handle the right compromise between the simplicity of the models and the complexity of the real world. For example, numerous computer vision algorithms have been proposed with the implicit assumptions that the observed surfaces are Lambertian and the illumination is uniform. These assumptions are only valid in customized environments. For applications such as the exploration of an outdoor environment the robustness of vision-based control schemes can be improved by using more realistic photometric models (including color information). Even though such models have already been used in the computer vision and augmented reality communities [45], [67] their applicability to real-time robotic tasks has not been much explored.

In the same way that sensor models currently in use in robotics are often too simple to capture the complexity of the real world, the hypotheses underlying the geometrical structure in the scene are often restrictive. Most of the methods assume that the observed environment is rigid [53]. For many applications like, for example, autonomous navigation in variable and dynamical environments, this assumption is violated. In these cases, distinguishing between the observed global (dominant) motion and the true motion, or even the deformations, of particular objects, is important.

More generally, the question is to estimate robustly and in real-time the information needed for the visual task. *Real-time processing of a complete model of a deformable environment (i.e. the tri-dimensional shape, the deformations of the surfaces, textures and colors and other physical properties that can be perceived by robotic sensors) has not yet been achieved*. Recent studies carried out on *visual tracking* (i.e. tracking of visual clues in the image without feedback control of the camera pose), using a stereo pair of cameras [68] or a single camera [41], are essentially concerned with parametric surfaces. To the best of our knowledge, the use of deformable visual information for navigation or feedback control has been limited to deformable contours [46], or simple articulated planar objects [71].

In many applications, using only one sensor may not be the optimal way to gather the information needed to perform the robot task. Many exteroceptive sensors provide complementary information (for example, unlike a single camera, a laser telemeter can directly measure the distance to an object), while proprioceptive sensors (odometry) are convenient to estimate local displacements of a robot. *We participate in the development of "intelligent" devices composed of several complementary sensors well-suited to the tasks involved in autonomous robotics.* Developing such sensors requires to solve different aspects of the problem : calibration, data representation, estimation and filtering. A theory for the proper integration of multi-sensor information within a general unified framework is still critically lacking.

3.2.2. Reliable robot localization and scene modeling

Most of the applications involving mobile robotic systems (ground vehicles, aerial robots, automated submarines,...) require a reliable localization of the robot in its environment. The problem of localization, given a map of the environment in the form of a set of landmarks or, conversely, the problem of constructing a map assuming that the vehicle's situation (position+orientation) is known, has been addressed and solved using a number of different approaches. A more attractive problem is when neither the robot path nor the map is known. Localization and mapping must then be considered concurrently. This problem is known as *Simultaneous Localization And Mapping*. In this case, the vehicle moves from an unknown location in an unknown environment and proceeds to incrementally build up a navigation map of the environment, while simultaneously using this map to update its estimated position. Two tutorials by Hugh Durrant-Whyte and Tim Bailey [40], [49] describe some of the standard methods for solving the SLAM problem but also some more recent algorithms. More recently, a new class of approaches has appeared based on *graphical inference technique* which represents the SLAM problem as a set of links between robot and landmarks poses, and formulates a global optimization algorithm for generating a map from such constraints [59], [69], [74]. Unfortunately, in the case of a robot exploring a large scale environment, such a method yields to dramatically increase the state vector during the motion. *We are investigating for well-founded methods which allow us to automatically introduce, if needed, a new local submap while preserving the consistency (in the sense of the probability) of the global map.*

The use of vision in SLAM provides a rich perceptual information compared to lasers and yields a low level of data association ambiguity. However real-time visual SLAM has only become possible recently with faster computers and ways of selecting sparse but distinct features. The main difficulty comes from the loss of the depth dimension due to the projective model of the camera. Consequently, monocular vision yields to address the specific configuration of *bearing-only slam*. In such a configuration, only the directions of sight of the landmaks can be measured. This leads to observability problems during the initialization. It is well-known in the computer vision community that specific motions of the camera, or very distant landmarks, lead also to observability problems. To overcome this type of problem, *delayed* landmark insertion techniques such as local bundle adjustment [48] or particle filtering [47] have been proposed. More recently *undelayed* approaches [50], [56], [72] have been investigated. These approaches generally rely on a probabilistic model of the depth distribution along the sight ray and require the use of particle filtering techniques or gaussian multi-hypothesis methods. Another approach relies on the use of dense representations instead of sparse ones based on landmarks. *We are applying these ideas to visual SLAM [70] by stating the problem in terms of the optimization of a warping function directly expressed in the image space*. The function parameters capture not only the geometrical and the photometrical aspects of the scene but also the camera motion. Robustness is enhanced by using a dense approach taking advantage of all the information available in the regions of interest instead of a sparse representation based on features like Harris or Sift points.

Nevertheless, solving the SLAM problem is not sufficient for guaranteeing an autonomous and safe navigation. The choice of the representation of the map is, of course, essential. The representation has to support the different levels of the navigation process : motion planning, motion execution and collision avoidance and, at the global level, the definition of an optimal strategy of displacement. The original formulation of the SLAM problem is purely metric (since it basically consists in estimating the Cartesian situations of the robot and a set of landmarks), and it does not involve complex representations of the environment. *However, it is now well recognized that several complementary representations are needed to perform exploration, navigation, mapping, and control tasks successfully. Alike several authors, we proposed [22] to use composite models of the environment which mix topological, metric, and grid-based representations.* Each type of representation is well adapted to a particular aspect of autonomous navigation : the metric model allows one to locate the robot precisely and plan Cartesian paths, the topological model captures the accessibility of different sites in the environment and allows a coarse localization, and finally the grid representation is useful to characterize the free space and design potential functions used for reactive obstacle avoidance. However, ensuring the consistency of these various representations during the robot exploration, and merging observations acquired from different viewpoints by several co-operative robots, are difficult problems. This is particularly true when different sensing modalities are involved. New studies to derive efficient algorithms for manipulating the hybrid representations (merging, updating, filtering...) while preserving their consistency are needed.

3.2.3. Exploration strategy and reactive navigation

The exploration of an unknown environment relies on a robot motion strategy which allows to construct a complete representation of the environment in minimal time or, equivalently, with displacements of minimal lengths. Few works have addressed these aspects so far. Most exploration approaches [44], [55] use a topological representation like the *Generalized Voronoï diagram (GVD)*. Assuming an infinite range for the sensors, GVD provides an aggregated representation of the environment and an elegant means to solve the optimality problem. Unfortunately, the usual generalized Voronoï diagram, which is based on the L_2 metric, does not cope well with real environments and the bounded range of the sensors used in robotic applications. Building topological representations supporting exploration strategies in real-time remains a challenging issue which is pursued in AROBAS.

For large-scale environments and long-time survey missions, the SLAM process can rapidly diverge due to the uncertainties and the drift inherent to dead reckoning methods, and the unavailability of absolute position measurements (as provided, for example, by a GNSS whose drawback is that it is not operational everywhere nor always). The problem of motion control is rarely considered as a constitutive part of the SLAM problem. We advocate that autonomous navigation and SLAM should not be treated separately, but rather addressed in an unified framework involving perception, modeling, and control. Reactive navigation and sensor-based control constitute the core of our approach. Sensor-based control, whose design relies on the modeling of the interactions between the robot and its nearby environment, is particularly useful in such a case. We show in simulation and experimentally [21] that embedding the SLAM problem in a sensor-based control framework acts as adding constraints on the relative pose between the robot and its local environment. In other words, the sensor-based control approach allows to guarantee, under certain observability conditions, a uniformly bounded estimation error in the localization process. *We pursue our research work on the design of navigation functions in order to, at a reactive control level, ensure collision-free robot motions and, at the navigation level, implement a (topologically) complete exploration of the environment in autonomous mode.*

3.3. Robot modeling and control

Since robotic, or "robotizable", mechanisms are structurally nonlinear systems which, in practice, need to be controlled in an efficient and *robust* manner, the project AROBAS has a natural interest and activities in the domain of Automatic Control related to the theory of control of nonlinear systems. Nonlinear control systems can be classified on the basis of the stabilizability properties of the linear systems which approximate them around equilibrium points. Following [39], an autonomous controllable nonlinear system is called *critical* when the corresponding linearized systems are not asymptotically stabilizable (and therefore not controllable either). Whereas local stabilizers for non-critical systems can often be derived from their linear approximations, one has to rely on other –truly nonlinear– methods in the case of critical systems.

For robotic applications, one is concerned in the first place with the design of feedback laws which stabilize state-reference trajectories in the sense of ensuring small tracking errors despite adverse phenomena resulting from modeling errors, control discretization, measurement noise,...

The set of critical systems strictly encompasses the one of controllable driftless systems affine in the control input (e.g. kinematic models of *nonholonomic wheeled vehicles*). Most of the existing literature on the subject has focused on these latter systems due to their well delimited and understood structural properties. On the other hand, nonlinear control-affine systems with a drift term which cannot be removed without rendering the system uncontrollable have been much less studied, whereas many locally controllable *underactuated mechanical systems* (e.g. manipulators with non-actuated degrees of freedom, hovercrafts, blimps, submarines,...) belong to this category of critical systems. However, there exist also underactuated mechanical systems which are not critical in the sense evoked above. Such is the case of flying machines with vertical take-off capabilities (helicopters, VTOL devices,...) whose linear approximations at an equilibrium are controllable due to the action of an external field of forces (the field of gravity, in the present case). Understandably, the control techniques used for these systems heavily rely on this property eventhough,

mathematically, the absence of such a field would not necessarily render the system itself (by opposition to its linear approximation) uncontrollable. This latter observation is important because it means that not all the structural controllability properties of the system have been exploited in the control design. This also implies that general control methods developed for critical systems could be applied to these non-critical systems, with their performance being less critically dependent on the existence and modeling of an external "stabilizing" field. To our knowledge, this research direction has never been explored before.
To summarize, the problem of control of critical nonlinear systems is relevant for most robotic devices other than fully-actuated holonomic manipulators. It is, of course, also relevant for other physical systems presenting similar structural control properties (an example of which are induction electrical motors). We have been advocating for a few years that it needs to be investigated further by developing new control design paradigms and tools. In this respect, our conviction is based on a certain number of elements, a summary of which follows.

- *Asymptotic stabilization of an equilibrium combining fast convergence (say exponential) and a degree of robustness similar to what can be achieved for linear systems (e.g. stability against structured modeling errors, control discretization, time-delays, and manageable sensitivity w.r.t. noise measurement,...) has never been obtained.* Studies that we, and a few other researchers, have conducted towards this goal [42], [60], [66] have been rewarded with mitigated success, and we strongly feel now that no solution exists: basically, for these systems, fast convergence rules out robustness.
- It is known from [73] that asymptotic stabilization of *admissible* state trajectories (i.e. trajectories obtainable as solutions to the considered control system) is "generically" solvable by using classical control methods, in the sense that the set of trajectories for which the linear approximation of the associated error system is controllable is dense. Although this is a very interesting result which can (and has been) thoroughly exploited in practice, this is also a delusional result whose limitations have insufficiently been pondered by practitioners. The reason is that it tends to convey the idea that all tracking problems can be solved by applying classical control techniques. The application of *Brockett's Theorem* [43] to the particular case of a trajectory reduced to a single equilibrium of the system indicates that no smooth pure-state feedback can be an asymptotical stabilizer, and thus clearly invalidates this idea. If an asymptotic stabilizer exists, it has to involve a non-trivial dynamic extension of the initial system. Time-varying feedbacks that we have been first to propose [18] to solve this type of problem in the case of nonholonomic systems constitute an example of this. *However, solving the problem for fixed equilibria still does not mean that "any" admissible trajectory can be asymptotically stabilized, nor that there exists a "universal" controller, even a complicated one, capable of stabilizing any admissible trajectory –whereas simple solutions to this latter problem are well-known for linear systems. This lack of completude of the results underlies severe practical implications which have not been sufficiently addressed.*
- For instance, the non-existence of a "universal" stabilizer of admissible (feasible) trajectories has been proven in [58] in the case of nonholonomic systems. This result is conceptually important because it definitively ruins the hope of finding a complete solution to the tracking problem (in the usual sense of ensuring asymptotic stabilization), even for the simplest of the critical systems.
- *To our knowledge, the problem of stabilizing* non-admissible *trajectories has never been addressed systematically, even in the case of fully-actuated nonholonomic systems, except by us recently.* A decade of active research devoted to the control of these systems (in the 1990's) had left this issue wide-open, eventhough it was known that, for a nonholonomic driftless system, the property of local controllability implies that any continuous non-admissible trajectory in the state space can be approximated with arbitrary good precision by an admissible trajectory. While several open-loop control methods for calculating such an approximation have been proposed by various authors [57],[17], *practical* stabilization of non-admissible trajectories –the feedback control version of the problem– seems to have been completely "occulted" by the problem of asymptotic stabilization of admissible trajectories.

- The range of feedback control design methods for nonlinear systems, especially those based on geometrical concepts, is limited and needs to be enlarged. Existing methods are often inspired by ideas and techniques borrowed from linear control theory. Whereas this makes good sense when the system is non-critical (including feedback linearizable systems), we contend that critical systems, being structurally different, call for revisiting and adapting the basic concepts and objectives on which control design methods lean. The notion of practical stabilization is an example of such an adaptation.

The objective of *practical stabilization* is weaker than the classical one of asymptotic stabilization: any asymptotical stabilizer is a practical stabilizer –whereas the converse is not true. However, this objective is not “much” weaker. In particular, instead of ensuring that the error converges to zero, a practical stabilizer ensures that this error is ultimately bounded by some number which can be as small as desired (but different from zero). We assert that this “small” difference in the objective changes everything at the control design level in the sense that none of the obstructions and impossibilities evoked previously holds any more: fast convergence to a set contained in a small neighborhood of the desired state can be achieved in a robust fashion, universal practical stabilizers of state trajectories exist, and, moreover, these trajectories do not have to be admissible. Furthermore, by accepting to weaken the control objective slightly, the set of control solutions is considerably enlarged, so that new control design methods can be elaborated. One of them is the *Transverse Function* approach that we have initiated a few years ago and that we continue to develop. It is based on a theorem, first published in [10], which states the equivalence between the satisfaction of the Lie Algebra Rank Condition (LARC) by a set of vector fields and the existence of particular (bounded) periodic functions whose infinitesimal variations are *transversal* to the directions associated with these vector fields. For control purposes, the time-derivatives of the variables on which such transverse functions depend can be used as extra control inputs which facilitate the control of systems whose dynamics are either completely (the case of nonholonomic systems) or partially (the case of underactuated systems) driven by the vector fields with which the transverse function is associated. In the case of mechanical systems, these new control inputs are directly related to the frequency of the “manœuvres” that the system has to perform in order to track a given reference trajectory. With this interpretation in mind, one can say that the approach provides a way of adapting the frequency of the manœuvres automatically.

We have first experimented feedback controllers derived with this approach on our laboratory unicycle-type mobile robot with the goal of tracking an omnidirectional vehicle (target) observed by a camera mounted on the robot (vision-based tracking). To our knowledge, this experiment is still unique in its kind. Results that we have obtained show a net improvement with respect to earlier attempts that we had made, based on the use of time-varying feedback techniques [75]. Theoretically, the approach can be applied to any nonholonomic vehicle –car-like vehicles without or with trailers, in particular [14].

More recently, we have adapted it to the problem of controlling nonholonomic mobile manipulators, i.e. manipulators mounted on nonholonomic mobile platforms, and have derived a general methodology for the coordinated motion of this type of robot [4]. It is based on the concept of *omnidirectional companion frame* which basically allows to control the mobile platform as if it were omnidirectional. Feedback control laws devised with this methodology have properties never demonstrated before, such as the possibility of ensuring the perfect execution of a manipulation task on a moving object whose motion is not known in advance, with the insurance that the manipulator will never collide into its joint-limits.

Even more recently, we have started to extend the approach to the control of critical underactuated mechanical systems, a problem which is more difficult than the control of fully-actuated nonholonomic systems due to the necessity of including dynamical effects in the modeling equations of the system, yielding a drift term which cannot be treated as a perturbation which can be pre-compensated. For these systems, the objective is again to practically stabilize any desired trajectory (admissible, or not) defined in the configuration space. To our knowledge, this problem had never been solved before, even for the simplest critical underactuated system (namely, the 3-dimensional second-order chained system). Although we have already much progressed on this subject, and devised a control design method which applies to classical examples of critical underactuated mechanical systems involving a single rigid body [13], many aspects of the problem have not been explored yet, or need to be studied further. Several are related to the definition and exploitation of criteria to qualify and compare different implementations of the control design method, such as the property of making velocities tend to zero when the reference trajectory is reduced to a fixed-point. Others concern the applicability and usefulness of the approach when the system is not critical (due to the action of dissipative/friction forces combined with the gravity field, in particular).

Robustness is a central and vast issue for feedback control. Any feedback control design approach has to be justified in terms of the robustness properties which are associated with it. In the case of advanced robotic applications based on the use of exteroceptive sensors, robustness concerns in the first place the capacity of dealing with the imprecise knowledge of the transformations relating the space in which sensor signals live to the Cartesian space in which the robot evolves. A vast literature, including several chapters of [17] and a large part of the publications on vision-based control, has addressed this issue in the case of fully actuated holonomic manipulators. Comparatively, very little has been done on this subject in the case of nonholonomic and underactuated mobile robots. We have thus initiated studies in order to figure out i) how feedback control schemes based on the use of transverse functions can be adapted to the use of exteroceptive sensors when the above mentioned transformations are not known precisely, and ii) how robust the resulting control laws are. Initial results that we have obtained are encouraging [62], but the complexity of the analyses also tells us that future research efforts in this direction will have to rely much on simulation and experimentation.

3.4. Transverse research themes

3.4.1. Robustness of sensor-based control

Interacting with the physical world requires to appropriately address perception and control aspects in a coherent framework. Visual servoing and, more generally, sensor-based robot control consists in using exteroceptive sensor information in feedback control loops which monitor the dynamic interactions between a robot and its environment. Since the beginning of the 1990's, a lot of work have been done on sensor-based control in the case of fully-actuated holonomic systems. The control of these systems is much simplified by the fact that instantaneous motion along any direction of the configuration space is possible and can be monitored directly [53]. *However, this assertion is not true in the case of critical or under-actuated systems like most ground, marine or aerial robots. New research trends have to be investigated to extend the sensor-based control framework to this kind of mechanisms.*

Robustness is needed to ensure that the controlled system will behave as expected. It is an absolute requirement for most applications, not only to guarantee the good execution of the assigned tasks, but also for safety reasons, especially when these tasks involve direct interactions with humans (robotic aided surgery, automatic driving,...). A control law can be called "robust" if it is able to perform the assigned stabilization task despite modeling and measurement errors. Determining the "size" of "admissible" errors is understandably important in practice. However, carrying out this type of analysis is usually technically quite difficult. For standard vision-based control methods [53], only partial results have been obtained in a limited number of cases [51]. Recently, we have studied the robustness of classical vision-based control laws (relying on feedback linearization) [3] with respect to uncertainties upon structure parameters, and proved that small estimation errors on these parameters can render the control laws unstable [61]. This study has been extended to central catadioptric cameras [63]. *One of our objectives is to develop tools for the evaluation of robustness properties of sensor-based control schemes, for generic vision devices (by extending existing results).*

4. Application Domains

4.1. Panorama

Advanced robotics offers a wide spectrum of 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, automatic driving, observation and surveillance by aerial robots,... without forgetting emerging and rapidly expanding applications in the domains of robotic domestic appliances, toys, and medicine (surgery, assistance to handicapped persons, artificial limbs,...). A characteristics of these emerging applications is that the robots assist, rather than compete with, human beings. Complementarity is the central concept. The robot helps the operator in taking decisions or extending his physical capacities. 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.

We are currently involved in a certain number of applications, a list of which follows. Our participation in these applications is limited to the transfer of methods and algorithms. Implementation and validation are left to our partners.

- *Ground robotics :* Since 1995, INRIA has been promoting research in the field of the intelligent transport systems. 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) within large and evolutive structured environments. The ANR TOSA project CITYVIP beginning in 2008 follows the Predit project MOBIVIP, which ended in 2006.

  Finally, since 2004 we have participated in two projects conducted by the DGA (French Defense) in the field of military robotics. PEA MINIROC is a typical SLAM problem based on sensory data fusion, complemented with control/navigation issues. It addresses on-line indoor environment exploration, modeling and localization issues with a mobile robot platform equipped with multiple sensors (laser range-finder, omnidirectional vision, inertial gyrometer, odometry). As a follow-up to the project PEA MINIROC, the project RAPID CANARI aims at extending robustness of indoor SLAM by merging visual and range sensors. On the other hand, PEA TAROT addresses autonomy issues for military outdoor robots. Our contribution focuses on the transfer and adaptation of our results in real time visual-tracking for platooning applications to operational conditions.

- *Aerial robotics* has grown in importance for us these last few years. Collaborations with the Robotics and Vision Group at CenPRA in Campinas (Brazil) and the Mechanical Engineering Group at IST in Lisboa (Portugal) are pursued towards the development of an unmanned airship for civilian observation and survey missions. Potential end-user applications for such vehicles are either civilian (environmental monitoring, surveillance of rural or urban areas, rescue deployment after natural disasters...) or military (observation or tactical support...). The experimental setup AURORA (*Autonomous Unmanned Remote Monitoring Robotic Airship*) consists of a 9 meters long airship instrumented with a large set of sensors (GPS, Inertial Navigation System, vision,...) located in Campinas. Vision-based navigation algorithms are also studied in the FP6 STREP EUROPEAN PROJECT PEGASE, led by Dassault, which is devoted to the development of embarked systems for autonomous take-off and landing when dedicated airport equipments are not available.

  Aerial vehicles with vertical take-off and manœuvering capabilities (VTOLs, blimps) also involve difficult control problems. These vehicles are underactuated and locally controllable. Some of them are critical systems in the sense of the non-controllability of their linearized equations of motion, even under the action of gravity (like blimps in the horizontal plane), whereas others are not due to this action (like VTOLs). Our objective is to propose control strategies well suited to these systems for different stabilization objectives (like e.g. teleoperation or fully autonomous modes) [5]. For example, a question of interest to us is to determine whether the application of control laws derived with the transverse function approach is pertinent and useful for these systems. The main difficulties associated with this research are related to practical constraints. In particular, strong external perturbations, like wind gusts, constitute a major issue for the control of these systems. Another issue is the difficulty to estimate precisely the situation of the system, due to limitations on the information that can be obtained from the sensors (e.g. in term of precision of the measures, or of frequency of the data acquisition). We have addressed these issues in two projects. The first one is the ANR project SCUAV (Sensory Control of Unmanned Aerial Vehicles) involving several academic research teams and the french company BERTIN TECHNOLOGIES. The second one is the Eco-Industrie project RAPACE which involves several industrial and academic partners and is managed by the french company GEOCEAN.

5. Software

5.1. Experimental Testbeds

Methodological solutions to the multi-faceted problem of robot autonomy have to be combined with the ever present preoccupation of robustness and real-time implementability. 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 AROBAS –and thus maintain the coherence and unity of the project-team–, but also to understand the core of the problems on which research efforts should focus in priority. The instrumented indoor and outdoor wheeled robots constitute a good compromise in terms of cost, security, maintenance, complexity and usefulness to test much of the research conducted in the project-team and to address real size problems currently under investigation in the scientific community. For the next few years, we foresee on site testbeds dedicated to ground robotic applications (figure 1 Left and Center).

- *HANNIBAL Indoor mobile robot*
  Our cart-like platform, built by Neobotix can operate on flat surfaces, in both indoor and outdoor environments. This platform is equipped with the various sensors needed for SLAM purposes, autonomous navigation and sensor-based control. With its programming further developed to become user-friendly, it has become one of the team's main testbeds for fast prototyping of perception, control and autonomous navigation algorithms.
- *CyCab Urban electrical car*
  Two instrumented electrical cars of the *CyCab* family are destined to validate researches in the domain of *Intelligent urban vehicle*. *CyCabs* are used as experimental testbeds in several national projects.
- *Hexacopter VTOL vehicle*
  A basic version of this machine was recently acquired from Mikrokopter Inc.(Germany) by our colleagues (T. Hamel, G. Ducard, M.-D. Hua) from the SIS (Signal, Images et Systèmes) research pole at I3S-UNSA-CNRS. It has a diameter of 90cm, weights about 1.5 kg, and can carry a payload up to 1.5 kg (figure 1 Right). The flight time autonomy varies between 6mn and 18mn, depending on the payload, and it can be extended provided that the battery capacity is extended accordingly. The machine's external envelope has been modified for safety reasons. Initial flight tests have been conducted, and the aircraft is currently being equipped with various sensors (GPS, accelerometers, gyrometers, camera,...). We are working with our colleagues from I3S to control this vehicle with the aim of providing it with large autonomy capabilities and robust performance. It is also a benchmark to validate various estimation/control issues that we are currently investigating.

6. New Results

6.1. Perception and autonomous navigation

Participants: Patrick Rives, Pascal Morin, Andrew Comport, Alexandre Chapoulie, Gabriela Gallegos, Cyril Joly, Maxime Meilland, Glauco Scandaroli.

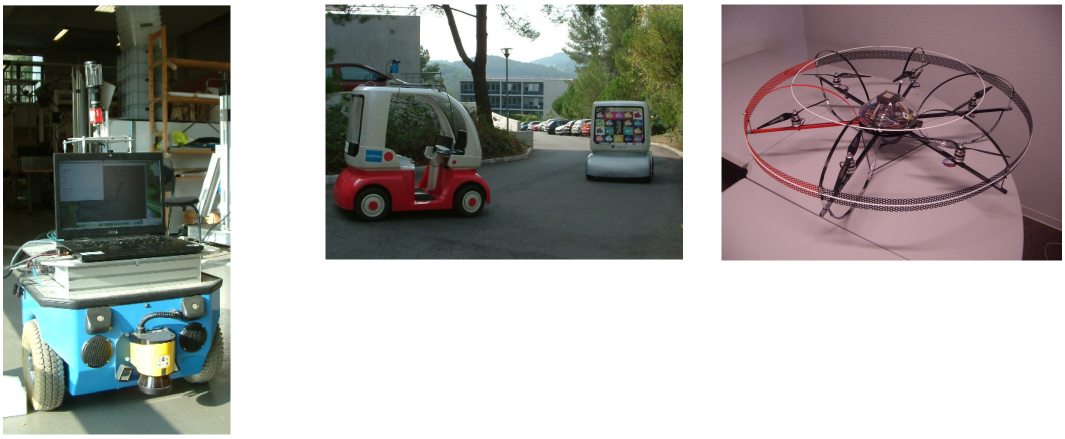

Figure 1. Left: The Hannibal platform.– Center: The Cycab vehicle. –Right: Hexacopter

6.1.1. Indoor SLAM: Self-calibration of the camera frame with respect to the odometry frame

Fusing visual data and odometry information is a standard technique to improve the robustness of the SLAM solution. Odometry data is considered as an input of the motion prediction equation while the visual data constitutes the filter observation. However, such method requires that the system is well calibrated: the pose of the camera frame with respect to the odometry frame has to be known. Usually, this pose is directly obtained by an hand made measurement yielding to incorrect values. We propose a new self calibration method to get these calibration parameters automatically. In practice, the state in the SLAM formulation is augmented with the unknown camera parameters (with respect to the odometry frame). This method requires to adapt a few Jacobians with respect to the original SLAM algorithm which assumes that these parameters are known. The accuracy and the stability of the estimation scheme clearly depends on the observability and the conditioning properties of the new system.

In 2010, we presented results in the case where the camera frame location has only 3 degrees of freedom (two translations and a rotation with respect to the vertical z axis). This year, these results were extended to the full calibration problem. As in the previous case, we assume that the robot is moving on a horizontal ground and observes 3D landmarks from the images delivered by the on board camera. The five parameters introduced by the calibration problem - 2 translations and 3 rotations (only 2 translations since the z component is not observable due to the planar motion of the robot) - are estimated simultaneously in addition to the "classical" SLAM parameters. The implementation of the algorithm is based on a *Smoothing And Mapping* (SAM) approach which computes a solution by considering the whole trajectory (instead of only the current pose as with the EKF approach).

As a theoretical result, we prove that this augmented system remains **observable** if and only if the curvature of the robot trajectory changes. This analysis was validated on real data with our indoor robot. Fig. 2 shows the mobile platform and the camera. It can be seen that an important rotational offset was added on the camera to test the capability to deal with large rotational values (the parameters are initialized with identity). Results are provided on Fig. 3-4 and table 1. They show that the trajectory and the map seem consistent; moreover, the algorithm was able to correct the odometry drift (green trajectory on Fig. 3). Then, the observability analysis was validated since the estimation of the camera frame parameters begins when there is a significant change in the radius of curvature of the trajectory (see the confidence bounds on Fig.4). Finally, the estimation of these parameters was consistent with the ground truth (table 1). These results were presented at IROS'11 conference [30].

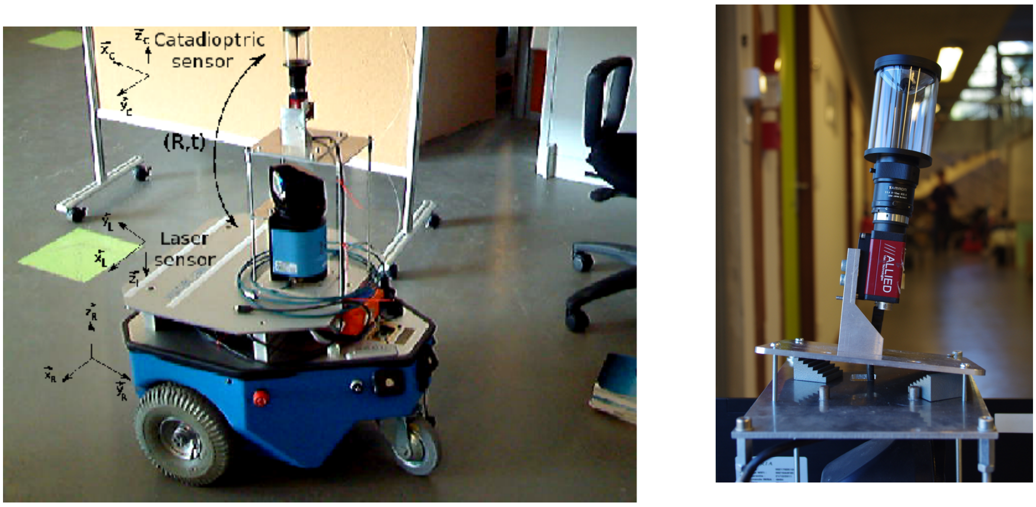

Figure 2. Left: Robot used for the experiment – Right: The omnidirectional camera mounted with a rotational offset

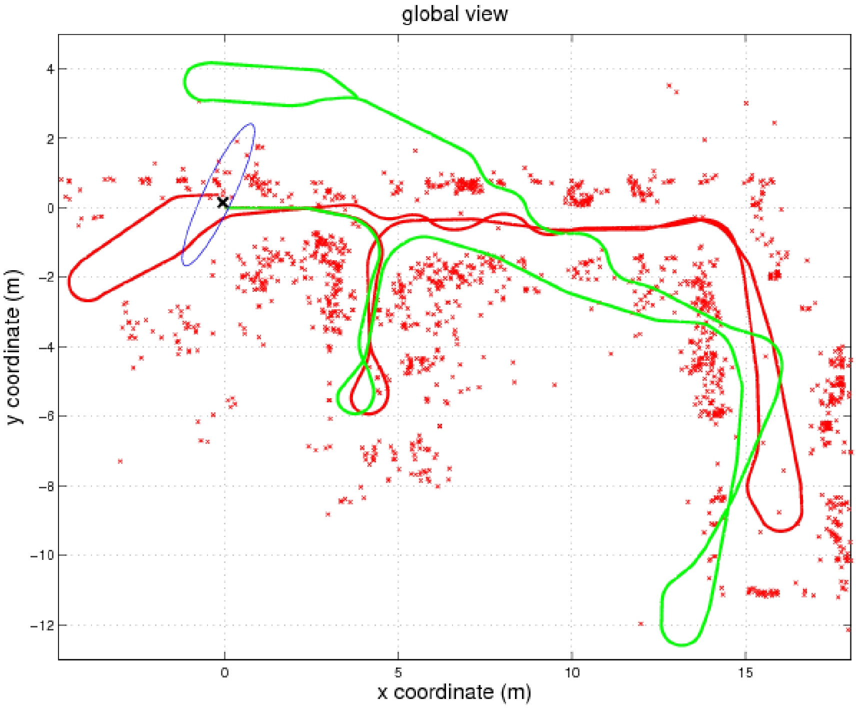

Figure 3. Red: trajectory and map provided by the algorithm — Green: odometry integration — Black cross: end of the trajectory — Blue: 99% confidence region for the last robot position

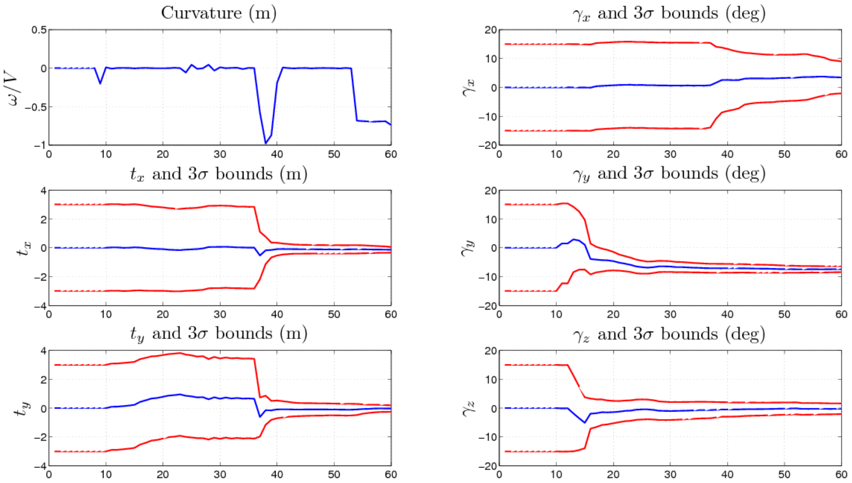

Figure 4. Evolution of the curvature and the estimation of the camera parameters

Table 1. Numerical results concerning the camera parameters

		Reference	Estimation	3σ bounds
Camera param.	t_x (m)	-0.16	-0.149	$[-0.165, -0.132]$
	t_y (m)	-0.35	-0.38	$[-0.064, -0.013]$
	γ_x (deg)	6.05	6.609	$[6.276, 6.942]$
	γ_y (deg)	-7.34	-7.714	$[-7.889, -7.539]$
	γ_z (deg)	0	0.668	$[0.330, 1.007]$
Final Pose	x_{end} (m)	-0.06	-0.11	$[-1.32, 1.09]$
	y_{end} (m)	0.15	0.56	$[-1.76, 2.89]$
	θ_{end} (deg)	0	-1.18	$[-12.96, 10.58]$

6.1.2. Outdoor Visual SLAM

Safe and autonomous navigation in complex outdoor urban-like environment requires a precise and real time localization of the robot. Standard methods, like odometry, typically performed by wheel encoders or inertial sensors, are prone to drift and not reliable for large displacements. Low cost GPS stations are inaccurate and satellite masking effect happens too frequently due to corridor-like configurations. We develop a real time and accurate localization method based on vision only without requiring any additional sensor.

Our approach relies on a monocular camera on board the vehicle and the use of a database of spherical images of the urban scene acquired during an offline phase. This geo-referenced database allows us to obtain a robust "drift free" localization. Basically, the database is constituted of spherical images augmented by depth which are positioned in a GIS (Geographic information system). This spherical robot centered representation accurately represents all necessary information for vision based navigation and mapping ([26]). During the online navigation, the current vehicle position is computed by aligning the current vehicle camera view with the closest reference sphere extracted from the database.

A spherical augmented acquisition system has been developed and tested on our Cycab vehicle. This system is composed of six wide angle stereo cameras in overlap, which permits to extract depth information by dense correspondence. Since the depth is available, we are able to construct 360 degrees spherical images with a unique center of projection. Those 3D spheres are then used in an image-based spherical odometry algorithm to obtain the trajectory of the vehicle ([31]), fuse the spheres and construct the database.

During the online navigation, we consider a vehicle equipped with a simple camera (perspective, omnidirectional...). Here the aim is to register the current view on the closest sphere stored in the database. To achieve this we have developed a spherical image-based registration which allows efficient and accurate localization. But since the database of augmented visual spheres can be acquired under different illumination conditions than the online camera is experiencing, a robust algorithm combining model based localization and online visual odometry has been developed [32]. This method performs in real-time (45 Hz), and allows to handle large illumination changes and outliers rejection (see figure 5).

As a part of the ANR CityVIP project, the localization and mapping system has been successfully tested in Clermont Ferrand (France). A database of augmented images has been built along a learning trajectory. The aim was to automatically "replay" the learning trajectory using the database and a monocular camera. To avoid collisions and pedestrians, a laser was mounted on the front of the Cycab. The system was able to autonomously follow large scale trajectories (over 400 meters), in crowded urban environments (see figure 6).

6.1.3. Loop closure detection for spherical view based SLAM

Although more precise than the odometry computed from the wheels encoders, the visual odometry also suffers from the problem of drift when large displacements are performed. It is possible to correct this drift if the robot is capable to determine if the the place it is visiting has already been visited. re-observes a scene previously observed. This is often referred as the loop closure detection problem and several methods exist in the literature using perspective cameras. We develop new methods more reliable by exploiting the peculiar properties of spherical cameras.

Standard perspective cameras have a limited field of view leading to an incapability to encompass all the surrounding environment. This limitation of the field of view drastically limits the performances of visual loop closure algorithms. We propose to use spheres of vision computed by mosaicing images from 6 wide angle cameras mounted on a ring. Such a representation offers a full 360 °field of view and keeps the spherical image invariant to the changes in orientations (Figure 7).

Loop closure detection can be exploited in a SLAM context at two levels: firstly, in the metric representation to retro-propagate along the robot's trajectory the cumulative errors due to the drift, secondly, in the topological representation, to fusion in the graph representation the nodes corresponding to a same place.

Existing algorithms are not point of view independent: loop closures are detected uniquely when a place is revisited by the robot coming from the same direction but if the robot comes back in a different direction, the algorithms fail. Our solution relies on the presented spherical view and an efficient way of information

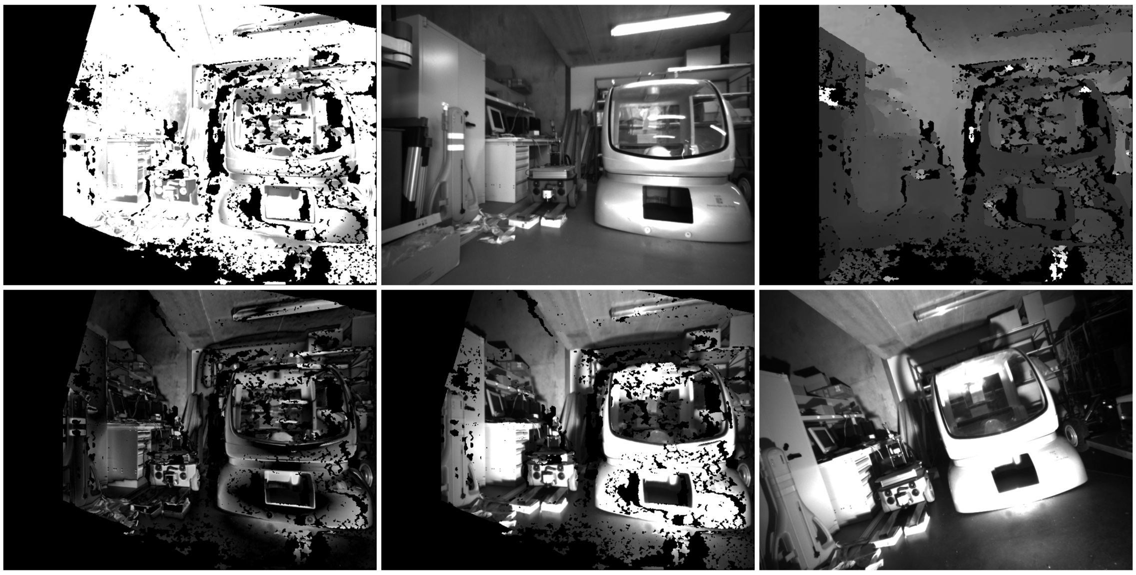

Figure 5. Top left, robust outliers weights. Top center, augmented reference image. Top right, reference depth-map. Bottom left, intensity error after alignment. Bottom center, registered image. Bottom right, original current image.

Figure 6. Autonomous driving.

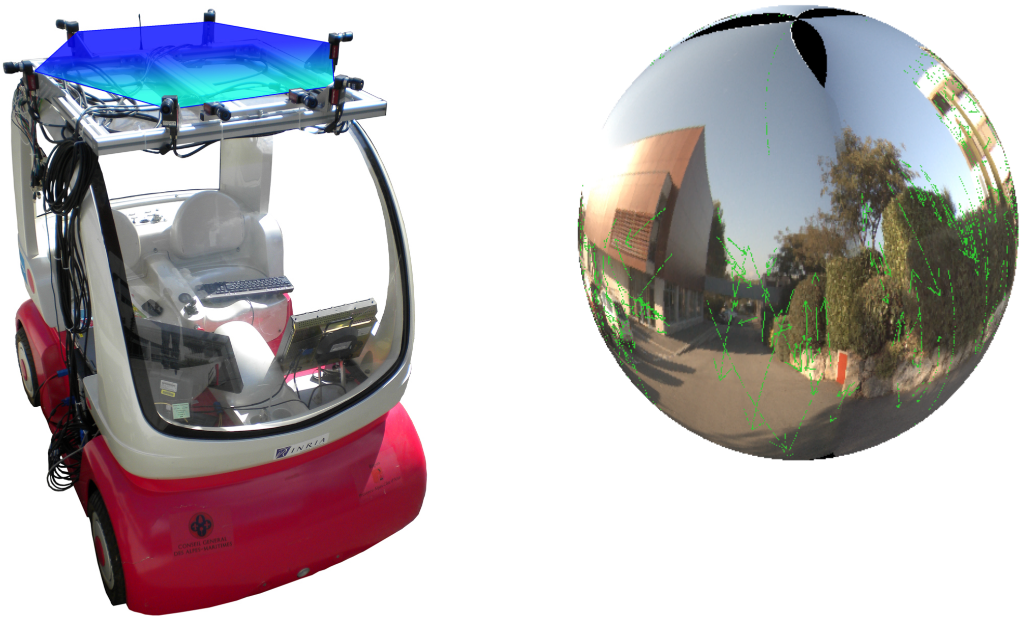

Figure 7. Spherical view acquisition

extraction from it. We extract local information describing the points of interest of the scene. We enhance this local information with a global descriptor characteristic of the distribution of the points of interest over the sphere thereby describing the environment structure. These informations are used to retrieve the already visited places. Our algorithm performs well and is robust to the point of view variation [27]. This has led to an accepted paper at OMNIVIS 2011.

The figure 8 below presents obtained results. The trajectory is corrected (drift reduction) using the loop closure constraint. Red and green dots represent the loop closing places, they are linked by a red line.

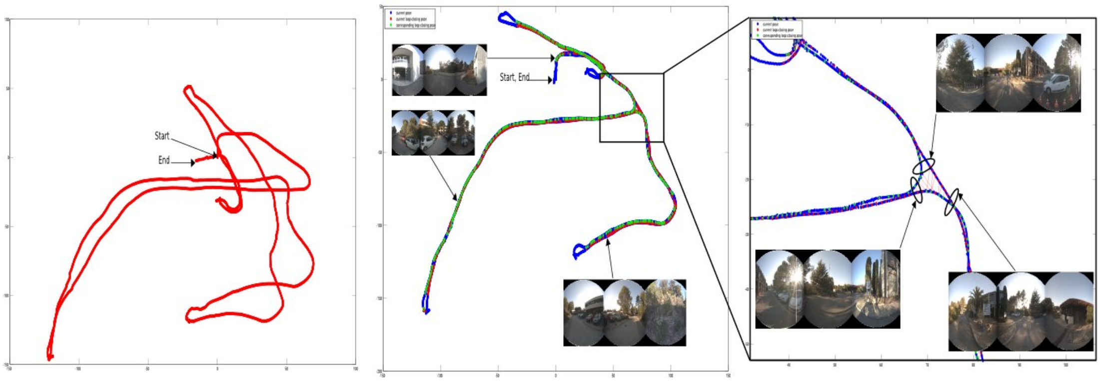

Figure 8. Loop closure detection and trajectory drift correction

6.1.4. Context-based segmentation of scenes

In a topological SLAM framework based on vision, the places are often represented by images gathered at regular time/distance intervals. It is nevertheless a meaningless representation in the context of topology. We would prefer a definition like "in front of a building" or "entrance of the campus" instead of "image number i". Places are thus a set of images we need to group. This is what we call context based segmentation. In order to achieve this segmentation a criterion for "changing place" is needed, we propose to evaluate the environment structure using a global spatial descriptor (computed on the spherical view) called GIST. The algorithm relies on a statistical process control monitoring for an out-of-control signal involving a changing place event. The algorithm still needs to be improved for better robustness on the localization of the changing place events when we come back on previous visited paths.
The figure 9 presents the preliminary results. On the bottom left is the similarity matrix of the images GIST while on the bottom right is the segmented trajectory followed by our robot.

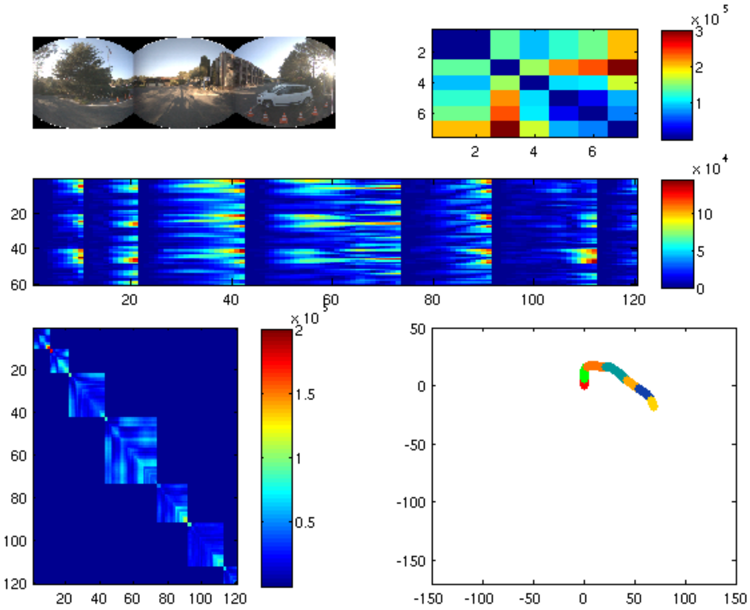

Figure 9. Context-based segmentation of scenes

6.1.5. Nonlinear observers for visual-inertial fusion with IMU-bias and camera-to-IMU rotation estimation

This work concerns the fusion of visual and inertial measurements in order to obtain high-frequency and accurate pose estimates of a visual-inertial sensor. While cameras can provide fairly accurate pose (position and orientation) estimates, the data acquisition frequency and signal processing complexity limit the capacities of such sensors in the case of highly dynamic motions. An IMU (Inertial Measurement Unit) can efficiently complement the visual sensor due to its high frequency acquisition, large bandwidth, and easy-to-process signals. IMU biases and calibration errors of the displacement between the camera frame and the IMU frame, however, can severely impair the fusion of visual and inertial data. Identification of these biases and calibration of this displacement can be achieved with dedicated measurement tools, but this requires expensive equipment and it is time consuming. We propose instead to address these issues via the design of observers. Last year, we had proposed a nonlinear observer to fuse pose and IMU measurements while identifying additive IMU biases on both gyrometers and accelerometers. We have extended this work to the self-calibration of the rotation between the pose sensor frame (camera) and the IMU frame. Simulation and experimental results have confirmed that this calibration significantly improves the final pose estimation and allows to process motions with faster dynamics. This work has been presented at the IROS conference in october [35]. It is a joint work with G. Silveira from CTI in Brazil. We are currently extending this result to include the self-calibration of the translation displacement between both sensors.

6.2. Control of mobile robots

Participants: Claude Samson, Pascal Morin, Minh-Duc Hua [Post Doc, I3S, CNRS-Univ. of Nice-Sophia Antipolis], Daniele Pucci, Glauco Scandaroli, Luca Marchetti, Tarek Hamel [Univ. of Nice-Sophia Antipolis].

6.2.1. New developments of the Transverse Function control approach

We are pursuing the development of the Transverse Function control approach for highly nonlinear systems via the application of the approach to challenging mechanical systems with various structural control properties.

6.2.1.1. Control of a redundant wheeled snake mechanism using transverse functions on $SO(4)$

The Transverse Function approach is applied to the control of a nonholonomic three-segments/snake-like wheeled mechanism, similar to the planar low-dimensional version of Hirose's Active Cord Mechanism (ACM) previously studied [65], but with two additional internal degrees of freedom (d.o.f.) whose actuation yields more flexible and efficient control solutions (see figure 10). From a theoretical point of view, these complementary d.o.f. modify the Control Lie Algebra of the system so that only first-order Lie brackets of the control vector fields are needed to satisfy the Lie Algebra Rank Condition (LARC). The fact that four independent (angular velocity) control inputs are used also implies for this system the existence of Transverse Functions (TF) defined on the six-dimensional special orthogonal group $SO(4)$. Several examples of mechanisms whose control involve TF defined on $SO(3)$ have been pointed out in the past [54], [64], [65]. Beyond the specific control problem addressed here, a motivation for the present study is to illustrate for the first time how functions defined on the larger set $SO(4)$ can be determined and used for the control of a physical system. This study is complemented with recalls concerning the parametrization of $SO(4)$ by pairs of *isoclinic* quaternions and with the derivation of complementary differential calculus relations associated with this parametrization. The results will soon be submitted for presentation at an international conference.

6.2.1.2. Control of three hooked vehicles with off-axle hitches

An extension of the study [65] performed last year on Hirose's Active Cord Mechanism (ACM) concerns the case when one of the wheeled-trains (the middle one, for instance) possesses actuators giving it tracting and rotating capacities (alike a unicyle-like vehicle), while the other two vehicles are passively hooked to this tracting vehicle. This type of actuation departs from the one of Hirose's Active Cord Mechanism for which the tracting capacity of the mechanism relies exclusively on the deformation of the system of vehicles via the control of the inter-connecting angles, and it makes an important difference at the control level. This system may also be seen as a unicycle-type vehicle with two trailers and off-axle hitches. Unlike the simpler hitch-on-axle case commonly addressed in the litterature, this system is not differentially flat and "complete" feedback solutions ensuring practical stabilization of any, feasible or non-feasible, trajectory remained an open issue. This actuation allows for the complete alignment of the three vehicles without going through actuation singularities, and for the asymptotic tracking of a reference frame moving along a straight line or a circle. On the other hand, in order to fully take advantage of the extra possibilities offered by it, one has to consider higher-order Lie bracket maneuvering motions that significantly complicate the feedback control design. The Transverse Function approach is applied using the fact that a dynamic extension of this two-control-inputs system is left-invariant on a 6-dimensional Lie group. Transverse functions calculated as the group product of "elementary" functions defined either on toruses or on $SO(3)$, and yielding feedback controls ensuring asymptotic stabilization of "feasible" reference trajectories under common "persistent excitation" properties (as in the case of classical feedback control solutions based on a linear approximation of the associated tracking

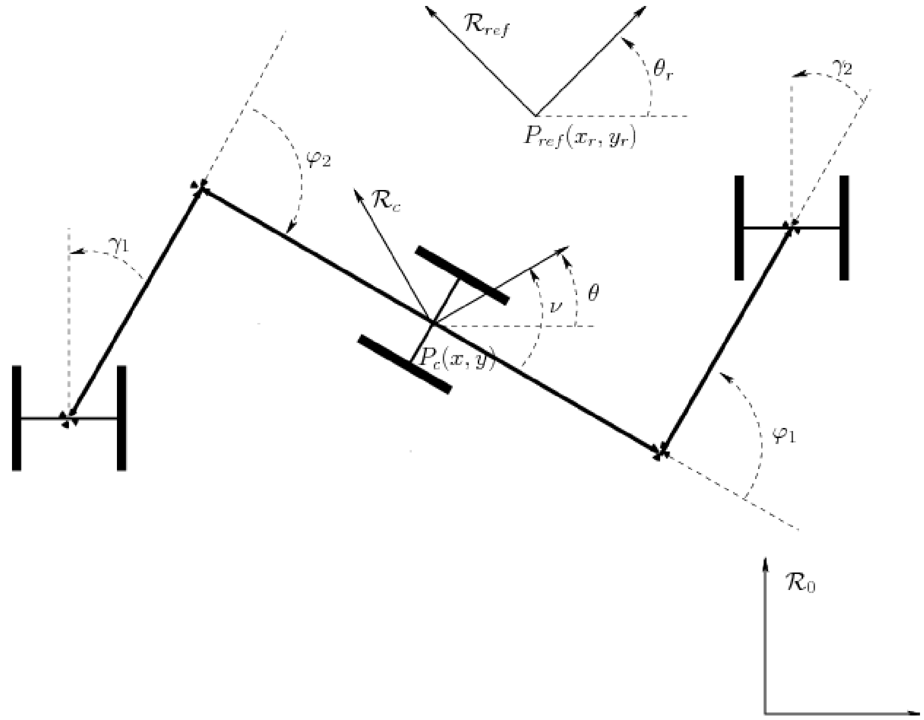

Figure 10. Three segments snake robot with two steering wheels. View from above

error system) are proposed. As usual, the superiority of the transverse function solution over more classical solutions comes from that it also applies to the case of non-feasible reference trajectories for which (practical) stabilization involves complex maneuvers. The results of this study will be submitted next year for presentation at an international conference.

6.2.1.3. Control of an extended trident-snake vehicle

This study is part of a thesis work on the control of non-standard nonholonomic mobile robots by W. Magiera under the dual supervision of Prof. K. Tchon (Wroclaw University of Technology) and C. Samson. This collaboration involves several long term visits of the PhD student at INRIA, starting this year (2 months), and for the next two years. This year's objective is to address a particularly challenging control problem and evaluate the possibilities offered by the Transverse Function approach to solve it. The system under consideration is based on the "common" trident snake mechanism [54] complemented with one, two, or three additional "passive" wheeled extensions, each of them subjected to the rolling-without-slipping constraint (see figure 6.2.1.3). Transverse Funstions solutions tested so far involve a mixt (product) of functions defined either on the torus, or on special orthogonal groups, and future improvements may involve the search for new transverse functions.

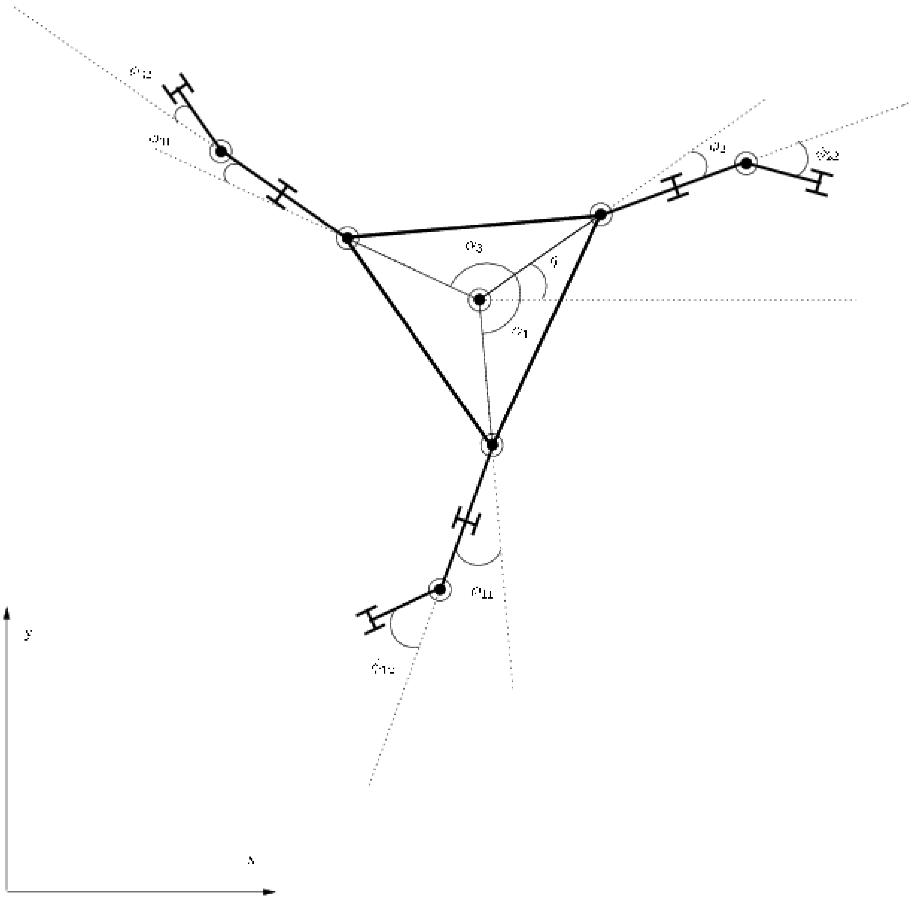

Figure 11. Trident-snake mechanism with passive extensions. View from above

6.2.2. Control of aerial vehicles

6.2.2.1. Vehicles subjected to lift forces

The development of a general theory for the control of underactuated (ground, marine, and aerial) vehicles whose main propulsion relies on a thrust force exerted in a single (vehicle's related) direction was continued this year. Part of this program, more specifically devoted to aerial vehicles, is the subject of D. Pucci's thesis research project. This year's focus was the prolongation of the work initiated last year on the modelling of lift forces and on their effects on the flight and control of aerial vehicles. Among the new results obtained on the subject, an extension and generalization of a previous feedback control strategy developed for spherically-shaped vehicles only subjected to drag forces [52], based on an "ideal" generic model of lift and drag forces associated with bi-symmetric wings, has been accepted for presentation at an international conference ([34]). The proposed solution involves a change of thrust control input in order to render the dynamics of the transformed system independent of the angle of attack associated with the vehicle's main wing. A weakness of the aforementioned model is that it does not account for the so-called *stall phenomenon*, which is an abrupt loss of lift when the angle of attack increases beyond a certain value called *stall angle*. Taking it into account adds considerable complexity to the vehicle's dynamics, especially in the case of a vehicle moving within a fluid endowed with a large Reynolds number for which the stall phenomenon can no longer be neglected. We showed that, although this phenomenon never forbids the existence of an attitude equilibrium given a desired reference velocity, the uniqueness of this equilibrium is not always granted. As a consequence, modifications of the desired velocity may result in the abrupt disappearance of an equilibrium so that the asymptotic stabilization of a desired velocity profile may become an ill-conditioned problem. To avoid this complication a possibility consists in characterizing "good" velocity profiles –associated, for instance, to transition maneuvers between hovering and high-velocity cruising– for which the existence of continuously changing equilibria is ensured. First results on this topic and research direction have been submitted for presentation to an international conference.

6.2.2.2. Nonlinear control of VTOL UAVs with uncertain position measurements

This work concerns the feedback control of VTOL UAVs (Vertical Take-Off and Landing Unmanned Aerial Vehicles). The objective is to asymptotically stabilize a reference equilibrium configuration with a "semi-global" convergence domain, i.e global convergence domain in position and semi-global in orientation, knowing that a global convergence domain in orientation cannot be obtained with continuous feedback laws due to the topology of the rotation space $\mathbb{SO}(3)$. Several solutions to this problem have been proposed in the past years, under the assumption that the pose (i.e. position and orientation) is completely known. This work concerns the case when the relation between the "position measurements" and the true position vector is uncertain. In practice, such uncertainties are related, e.g., to ill-calibrated sensors or to uncomplete knowledge of the environment in the case of proximetry sensors. It is assumed that position measurements are given by $\overline{p} = Mp$ where p is the true position error with respect to the reference position, and M is an unknown invertible matrix. As a first contribution, we propose a class of feedback laws that achieve semi-global stability of the equilibrium $p = 0$ for any matrix M that satisfies the stability criteria $\|M - I_3\| < \delta(k)$ where I_3 is the 3×3 identity matrix, δ is a strictly positive function, and k is the vector of control parameters. An explicit expression of the function δ is provided, thus relating the control parameters to the stability margin. The second contribution of this work is the application of this control approach to the visual servoing of VTOL UAVs with respect to a planar vertical structure (wall, etc). From the homography matrix that relates the current camera image to a reference image (taken at the reference pose), we derive a signal output of the form $\overline{p} = Mp$. The matrix M typically depends on unknown parameters but we show that a very rough knowledge of them is sufficient to design a stable controller based on the above-mentionned stability criterion. These results have been submitted for publication at an international conference. This is a joint work with H. de Plinval and P. Mouyon from ONERA Toulouse.

6.2.3. Development of an autonomous shopping cart

This work, which consists in developing a shopping cart with autonomy capabilities (automatic user following, obstacle avoidance, etc), is part of the national INRIA PAL project (Personally Assisted Living) which aims at developing robotic tools for disabled persons or elderlies.

The architecture of “Autonomous Shopping Cart” has been developed in three layers. The first one is responsible for connecting the services layer to physical (or virtual) devices. During this year, all necessary components to access the devices have been implemented:

- the Phidgets library wraps the API of Phidgets devices and abstracts the access to the peripherals on the wheelchair robot;
- the Hannibal library wraps the interface to access the Hannibal robot (through Carmen library);
- the Simulator library wraps the simulator interface.

All of them expose a common interface to the software modules. Thus, the higher components do not have to be changed if the test platform changes.

The second level is the core of this year’s work. It is composed by the Control module and Modeling module. The Control module aims at stabilizing the trajectory of the robot w.r.t a given reference motion. In practice, this reference motion corresponds to the cart user that needs to be followed, but it could be any virtual reference motion. A first implementation of the Control module has been made using Matlab software. The result is a Control library that contains two different methods for controlling the trajectory:

- position control only;
- full-state control (position+orientation).

These methods have been implemented in Matlab language and then converted in C++. The resulting library has been utilized within the Control module deployed on the robotic platform.

The main objective of the Modeling module is to detect the cart user within the sight of the sensors. This task is generally non-trivial, due to noise in the sensor signals and variations of the environment. For this reason a Multiple Hypothesis Tracker has been used to allow for the presence of several persons in the environment. The method uses the laser scans to extract potential persons and then a Selector algorithm extracts the best hypothesis for the cart user. This hypothesis is then converted into a virtual reference point given to the Control module for trajectory tracking.

The third layer is represented by the Behavior module. This component manages the other modules, starts and stops services on request, enables the initialization procedure and so on. As for now, it starts all modules and initiates the starting procedure. In particular, it selects the first person to be tracked, among possible candidates.

Experiments have been successfully conducted both on the mobile robot Hannibal and on the wheeled walking aid ANG (Assistive Navigation Guide) developed by the EPI Coprin.

7. Contracts and Grants with Industry

7.1. Industrial Contracts

7.1.1. DGA/Rapid CANARI

Participants: Patrick Rives, Cyril Joly.

This project aims at developping a full autonomous indoor mobile robot dedicated to survey missions. CANARI is a follow up to the previous *Programme d’Etude Amont: PEA MiniROC* funded by the *DGA (Délégation Générale de l’Armement)*. The partners are a PME Robopec and the company ECA as in MiniROC. ARobAS is in charge of the development of SLAM aspects that rely on the C. Joly’s PhD thesis results.

7.1.2. Eco-Industrie program RAPACE

Participants: Pascal Morin, Glauco Scandaroli.

This project concerns the development of an aerial vehicle with Vertical Take-Off and Landing capabilities, and its automatic control from visual and inertial sensors. Our participation is more specifically dedicated to the problem of estimating the "pose" (i.e. position and orientation) of the vehicle from visual and inertial measurements, and to controlling the system from these measurements.
Our partners are GEOCEAN (Aubagne), ACS (St Sulpice de Royan), AKA (Lisses), DELTY (Toulouse), HELICE (Paris), Ecole Centrale de Lille, Ecole Centrale de Marseille.

8. Partnerships and Cooperations

8.1. National Initiatives

8.1.1. ANR Tosa CityVIP

Participants: Patrick Rives, Andrew Comport, Maxime Meilland.

This project, in the continuation of the "Automated Road Scenario", focuses on low speed applications (<30 km/h) in an open, or partly open, urban context. The level of automatization can vary from limited driving assistance to full autonomy. An important effort is devoted to the use of on-board vision for precise vehicle localization and for urban environment modeling. This model is then used for automatic guidance by applying visual servoing techniques developed by the research partners.

Our partners are Lasmea (Clermont Ferrand), IRISA/Lagadic (Rennes), Heudiasyc (Compiègne), LCPC (Nantes), IGN/Matis (Paris), Xlim (Limoges), BeNonad (Sophia Antipolis)

8.1.2. Inria Large Scale Initiative Action PAL (Personaly Assisted Living)

Participants: Patrick Rives, Pascal Morin, Luca Marchetti.

ARobAS participates in the Large-scale initiative action Personally Assisted Living to develop technologies and services to improve the autonomy and quality of life for elderly and fragile persons. The purpose of LSIA PAL is to provide an experimental infrastructure, in order to facilitate the development of models, tools, technologies and concept demonstrations. Using the skills and objectives of the involved teams, four research themes have been defined: Assessing the degree of frailty of the elderly, Mobility of people, Rehabilitation, transfer and assistance in walking, and Social interaction. We are currently involved in the themes "Mobility of people" and " assistance in walking" through collaborations with the EPI Emotion and the Laboratoire "Handibio" (Toulon).

8.2. European Initiatives

8.2.1. Major European Organizations with which you have followed Collaborations

Instituto Superior Technico of Lisbon (Portugal);

Visual Slam and visual servoing of aerial vehicles.

8.3. International Initiatives

8.3.1. Visits of International Scientists

8.3.1.1. Internship

Wladyslaw Magiera a PhD student from the Institute of Computer Engineering, Control and Robotics, Wroclaw University of technology, Poland, has joined the team for three months from October 3 to December 2.

8.3.2. Participation in other International Programs

As a follow up to the long time collaboration between EPI ARobAS and the CTI/ in Campinas (Brazil), the project MuNave was accepted for funding in the *INRIA/CNPq Collaboration* framework (2010-2012). This project aims at investigating new research themes in perception and control for autonomous mobile robots. This year, one researcher of CTI has spent two weeks at INRIA. The visit of ARobAS members at CTI is planned during the first quarter of next year.

9. Dissemination

9.1. Animation of the scientific community

- P. Rives was a member of the Program Commitee of the following conferences: ICRA, IROS, OMNIVIS, RFIA, JNRR.
- P. Rives provided the Agence Nationale de la Recherche (ANR) and the Swiss National Science Foundation with expertise work.
- P. Rives is an expert for OSEO (Agence Nationale pour la Valorisation).
- P. Morin is an expert for the DGRI (Direction Générale pour la Recherche et l'Innovation).

9.2. International conferences

ARobAS members have presented their work at the following conferences:

- IEEE International Conference on Robotics and Automation (ICRA), Shangai, China, May 2011,
- 18th World Congress of the International Federation of Automatic Control (IFAC), Milan, Italy, August-September 2011,
- IEEE/RSJ International Conference on Intelligent Robots Systems (IROS), San Francisco, USA, October 2011,
- 11th workshop on Omnidirectional Vision, Camera Networks and Non-classical Cameras (OMNIVIS 2011), Barcelona, Spain, November 2011,
- First International Workshop on Live Dense Reconstruction from Moving Cameras In conjunction with the International Conference on Computer Vision (ICCV). Barcelona, Spain, November 2011,
- Australian Conference on Robotics and Automation, Monash University, Australia, December 2011,
- IEEE Conference on Decision and Control (CDC), Orlando, USA, December 2011.

9.3. National conferences

ARobAS members have presented their work at the following conferences:

- Periodic meetings of work groups of the CNRS Research Program (GDR) in Robotics.

9.4. Activities of general interest

- P. Rives is a member of the INRIA CE (Commission d'évaluation).
- P. Rives is a member of the executive committee of the CNRS Research Program (GDR) in Robotics.
- P. Rives was a member of the jury in charge of the recruitment of a professor in the 61ième section in Montpellier.
- P. Morin is a member of the "Commission des Utilisateurs des Moyens Informatiques de Recherche" (CUMIR) at INRIA Sophia-Antipolis until june 2011.

9.5. Teaching

- *Teaching :*

  Master ERASMUS : "Autonomous Navigation and SLAM (Simultaneous Localization and Mapping)", 8 hours course, (M2) , Ecole Centrale de Nantes, France, (P. Rives)

  Graduate School on Control Spring 2011 (EECI-GSCS-2011): "Control of highly nonlinear systems" , 30 hours Eq. TD, European Embedded Control Institute, Ecole Supérieure d'Electricité, France, (P. Morin and C. Samson).

  " Course on linear control , 10 hours Eq. TD, Ecole Polytechnique Universitaire of Nice (EPU), France, (P. Morin).

- *PhD & HdR*

  PhD in Progress: A. Chapoulie, "Navigation visuelle à grande échelle en milieu urbain", Université de Nice-Sophia Antipolis, 2009, supervisors : P. Rives, D. Filliat (ENSTA).

  PhD: G. Gallegos, "Exploration et navigation autonome dans un environnement inconnu", Ecole des Mines de Paris, June 17, 2011, supervisor : P. Rives.

  PhD in Progress: M. Meilland, "SLAM visuel et navigation autonome en environnement urbain", Ecole des Mines de Paris, 2008, supervisors : P. Rives, A. Comport.

  PhD in Progress: H. de Plinval, "Commande référencée vision pour drones hélicoptères", Ecole doctorale de Toulouse, 2009, supervisors : P. Morin, P. Mouyon (ONERA).

  PhD in Progress: D. Pucci, "Control of thrust-propelled vehicles", Université de Nice-Sophia Antipolis, 2009, supervisors : T. Hamel, C. Samson.

  PhD: A. Salazar, "Direct Self-Calibration of Central Catadioptric Omnidirectional Cameras" Ecole des Mines de Paris, September 6, 2011, supervisor : E. Malis.

  PhD in Progress: G. Scandaroli, "Fusion de données visuelles et inertielles pour l'estimation d'état et applications à la commande de drones", Université de Nice-Sophia Antipolis, 2009, supervisor : P. Morin.

- *Participation in Ph.D. and H.D.R committees* :
  - P. Rives participated in six Phd defense juries in France, one PhD defense jury in Zaragoza (Spain), two HDR juries.
  - Samson participated in one PhD defense jury and in the Portuguese Habilitation in Electrical and Computer Engineering of Prof. C. Sylvestre, IST-ISR, Lisbon.

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