INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team arobas

Advanced Robotics and Autonomous Systems

Sophia Antipolis - Méditerranée

Theme : Robotics

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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, 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

Ezio Malis left the ARobAS team earlier this year in order to start a company that commercializes the ESM tracking and Control Software which was originally developped within the EPI ARobAS. Currently, the start-up is in incubation within the INRIA structure EVOLUTION.

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 *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

Participants: Patrick Rives, Ezio Malis, Andrew Comport, Alexandre Chapoulie, Gabriela Gallegos, Cyril Joly, Maxime Meilland, Adan Salazar.

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], [70] 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 [55]. 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 [71] or a single camera [40], 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 [75].

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 recent tutorials by Hugh Durrant-Whyte and Tim Bailey [39], [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 [62], [72], [78]. 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], [59], [76] 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 [74] 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 [20] 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 [43], [58] 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 [19] 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

Participants: Claude Samson, Pascal Morin, Minh-Duc Hua, Tarek Hamel.

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 [38], 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 [41], [63], [68] 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 [77] 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* [42] 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 [16] 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 [61] 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 [60],[15], *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 [9], 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 [79]. Theoretically, the approach can be applied to any nonholonomic vehicle –car-like vehicles without or with trailers, in particular.

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 [12], 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 [15] 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 (constituting the core of a PhD work) 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 [66], 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

Participants: Ezio Malis, Pascal Morin, Patrick Rives, Claude Samson, Tiago Ferreira Goncalves, Melaine Gautier.

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 works have been done in 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 [55]. *However, this assertion is not true in the case of critical or underactuated 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 [55], 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 [64]. This study has been extended to central catadioptric cameras [67]. *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).*

3.4.2. Mimetic Approach to Sensor-based Navigation

Sensor-based robot tasks were originally designed in the context of manipulation, with the control objective stated in terms of positioning and stabilizing the end-effector of a manipulator with respect to a structured object in the environment. Autonomous navigation in an open indoor or outdoor environment requires the conceptualization and definition of new control objectives. To this aim, a better understanding of the natural facilities that animals and human beings demonstrate when navigating in various and complex environments can be a source of inspiration. Few works have addressed this type of issue with a focus on how to define navigation control objectives and formulate them mathematically in a form which can be exploited at the control level by application of methods and techniques of Control Theory. Numerous questions arise. For instance, what is the right balance between planned (open-loop) and reactive (feedback) navigation? Also, what is the relative importance of topological-oriented versus metric-oriented information during navigation? Intuitively, topological aspects encompassing the accessibility of the environment seem to play an important role. They allow for a navigation which does not heavily rely on the knowledge of Cartesian distances. For example, when navigating along a corridor, it is more important to have information about possibilities of access than calculating distances between walls precisely. The nature of the “percepts” at work in animal or human autonomous navigation is still poorly known and understood. However, it would seem that the implicit use of an ego-centered reference frame with one of its axes aligned with the gravitational direction is ubiquitous for attitude (heading and trim) control, and that specific inertial and visual data are somehow directly acquired in this frame. In [73], we have exploited a similar idea for the automatic landing of an aerial vehicule by implementing a visual feedback which uses features belonging to the plane at infinity (vanishing point and horizon line). *It is also probable that the pre-attentive and early cognitive vision emphasized by the Gestalt theory provide useful inputs to the navigation process in terms of velocity, orientation or symmetry vector fields. Each of these “percepts” contributes to the constitution of sub-goals and elementary behaviors which can be adaptatively inhibited or re-enforced during the navigation process. Currently, little is known about the way animals and humans handle these different, and sometimes antagonistic, sub-goals to produce "effective" motions. Monitoring concurrent sub-goals, within a unified sensor-based control framework, is still an open problem which involves both perception and control issues.*

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 project CITYVIP beginning in 2008 follows the Predit project *MobiVIP*, which ended in 2006.

  We are also involved in the ANR 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.

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 equiped with multiple sensors (laser range-finder, omnidirectional vision, inertial gyrometer, odometry). More recently, 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* will grow in importance for us. Existing collaborations with the Robotics and Vision Group at CenPRA in Campinas (Brazil) and the Mechanical Engineering Group at IST in Lisboa (Portugal) will be pursued to develop 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). 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). Currently, we address 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 involving several industrial and academic partners and leaded by the french company GEOCEAN.

5. Software

5.1. Introduction

Participant: Ezio Malis.

- ESM Tracking and Control Software. The software allows for visual tracking and servoing with respect to planar objects. It has been successfully tested on the Cycabs in a car platooning application. This sofware is distributed under license agreement. Ezio Malis left the ARobAS team earlier this year in order to start a company that develops and commercializes this software. Currently, the start-up is in incubation within the INRIA structure EVOLUTION.
- The OMNIDIRECTIONAL CALIBRATION TOOLBOX is a Matlab 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. The toolbox is freely available over the Internet [1].

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

5.2. Experimental Testbeds

Participants: Patrick Rives, Pascal Morin, Ezio Malis, Patrick Pollet, Thomas Arnould, Alexandre Chapoulie, Melaine Gautier.

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 communauty. For the next few years, we foresee on site testbeds dedicated to ground robotic applications (figure 1).

- *HANNIBAL cart-like platform*
  A new cart-like platform, built by Neobotix, was acquired last year to replace our old indoor mobile robot ANIS. It can operate on flat surfaces, in both indoor and outdoor environments. This platform will be equiped with the various sensors needed for SLAM purposes, autonomous navigation and sensor-based control. Once its programming is further developed to become user-friendly, it should be 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 researchs in the domain of *Intelligent urban vehicle*. *CyCabs* are used as experimental testbeds in several national projects.

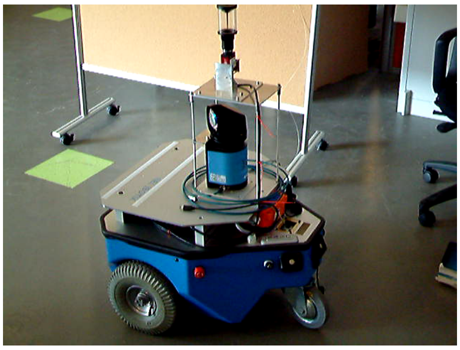

Figure 1. Left: The Hannibal platform. Right: The Cycab vehicle .

6. New Results

6.1. Advanced perception for mobile robotics

Participants: Ezio Malis, Pascal Morin, Adan Salazar, Rémi Desouche.

The realization of complex robotic applications such as autonomous exploration of large scale environments, observation and surveillance by aerial robots 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.

6.1.1. Self-calibration of central omnidirectional cameras

Omnidirectional cameras are important in areas where large visual field coverage is needed, such as motion estimation and obstacle avoidance. The advantage of omnidirectional cameras is primarily the ability to see a large part of the surrounding scene. However their practical use is often hindered by the calibration phase that can be time consuming and requires an experienced user. Accurate calibration of a vision system is necessary for any computer vision task requiring the extraction of metric information of the environment from 2D images. The present work was motivated by the desire to facilitate the adoption of central omnidirectional cameras in robotics via the avoidance of awkward calibration steps. Although omnidirectional camera calibration is well understood, no method allowing to robustly on-line self-calibrate any central omnidirectional camera is known. Most of the existent self-calibration methods are off-line and take into account a specific mirror (e.g. hyperbolic and parabolic) or a projection model (skewness, alignment, errors, ...). Therefore, this research concentrates on the on-line self-calibration of any central omnidirectional camera. Another motivation was the lack of a theoretical proof of the uniqueness of camera calibration. In most of the works on omnidirectional cameras calibration it has been observed that in the case of a non-planar mirror two images acquired from different points of view suffice to calibrate an omnidirectional camera. Even though, to our knowledge, no theoretical proof has yet been provided as for the uniqueness of the solution.

Three new results have been obtained this year:

6.1.1.1. Algorithm for the visual tracking of a plane with an uncalibrated catadioptric camera

An algorithm to efficiently track a plane in an omnidirectional image without requiring the prior calibration of the sensor has been proposed. The approach is very promising because the estimated parameters are integrated into a single global warping function. We deal with a non-linear optimization problem that can be solved for small displacements between two images like those acquired at video rate by a camera mounted on a robot. This algorithm can be very helpful in any application for which camera calibration is impossible or hard to obtain. This result is reported in the publication [30] presented at the IROS 2009 conference.

6.1.1.2. Direct approach for the self-calibration of catadioptric cameras

A simplification of the calibration phase, by providing a direct approach to the on-line self-calibration of catadioptric cameras, is proposed. The algorithm for the visual tracking of a plane is applied. We use several of the tracked views in order to calibrate the sensor. The proposed method is more flexible since it avoids tedious calibration steps. This should facilitate the adoption of omnidirectional sensors in robotics. This result is reported in the publication [31] presented at the OMNIVIS 2009 Workshop.

6.1.1.3. Proof of the uniqueness of the solution for the calibration of catadioptric cameras

This is an important contribution because no theoretical proof of the uniqueness of the solution for the calibration of catadioptric cameras had been proposed so far. We have formalized the calibration problem by using a unified model for catadioptric cameras that is valid for all central catadioptric systems. Besides, we have shown that the uniqueness of the solution can be derived from the solution of non-linear equations, which have been solved in the general case.

6.1.2. Fusion of visual and inertial data for pose estimation

Estimating the pose (i.e. position and orientation) of a vehicle with respect to its environment from onboard sensor's measurements is a fundamental problem for many robotic applications. In the case of aerial robotics for example, this problem is critical because fully autonomous control modes require an accurate estimation of the pose of the vehicle. For small vehicles, typically used in robotics, purely inertial solutions cannot be used due to the prohibitive cost and weight of the associated sensors. Solutions based on the use of GPS and low-cost/low-weight IMUs (Inertial Measurement Units) have been developed recently, but the pose estimation accuracy so obtained remains limited and, obviously, these solutions cannot be used when the GPS information is not available. For these reasons there is a growing interest in the development of vision based algorithms, which can provide alternative solutions with limited weight and cost. Due to the relatively low bandwith of visual sensors and problems associated with illumination changes, there is an interest in complementing artificial vision with an IMU. We have initiated this year a study on the fusion of visual and inertial data for pose estimation, with the objective of using this solution for aerial robotics applications. The approach that we have investigated consists in using the ESM algorithm [1] to obtain a first pose estimate that is used as a correction term in a nonlinear observer driven by the IMU measurements. The state of this observer is complemented so as to allow for the estimation of biases in the IMU measurements. This work, reported in [36], has been carried out as part of Rémi Desouche's internship. Glauco Scandaroli, who has just started a Ph.D. in our team, will take this study over.

6.2. Reliable robot localization and scene modeling

Participants: Patrick Rives, Cyril Joly, Gabriela Gallegos, Maxime Meilland, Andrew Comport.

6.2.1. Simultaneous Localization and Mapping (SLAM) :

In the *Simultaneous Localisation And Mapping* paradigm, the robot 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. Several issues have been addressed this year concerning 6dofs *Smoothing and Mapping (SAM)*,e.g. an alternative and more consistent formulation to the SLAM problem and a new approach aiming to fuse catadioptric vision and laser scanner in order to get a more reliable representation of the 3D environment.

6.2.1.1. 6dofs visual SAM:

Let us consider a standard 6dofs Bearing Only (BO) SLAM configuration, i.e. the robot in the 3D space observing 3D-landmarks with a camera. We consider the visual data only (we do not use odometry information). It is well known that a perspective camera only provides a measurement of the bearing of a landmark and not the distance. The distance can be computed by using several observations from different viewpoints. As a follow-up, the landmarks initialisation must be delayed when using the standard euclidian coordinates in the state representation (a criterion based on the parallax is generally used). However, landmarks can bring bearing information even though the depth is unknown. In order to use this information, Civera [44] introduced an alternative *not delayed* landmark representation, the *inverse depth* parameterization. This parametrization is usually used with standard EKF method and 6 components per landmarks are used in the filter. Unfortunately, such a parameterization is not minimal and instabilities in the estimation process can occur.

We have shown that in the *Smoothing and Mapping (SAM)* formulation, one can use only the 3 last components of the inverse depth parametrization in the estimated state. The unestimated part is used as equilibrium points to evaluate measurement functions and Jacobians. This can be done in a consistent way thanks to the SAM approach which stores and estimates at each step **all the trajectory** (the standard EKF does not estimate the full trajectory, so the 3 first components are estimated in the filter in the attempt to make them consistent during the next steps).

We tested our new approach with the data provided by an omnidirectional camera on a mobile robot. The trajectory includes an inclined plane in order to validate the 6dofs algorithm with real 3D data. Results are given on fig. 2 (top left, top right and bottom left). One can see that the trajectory is very accurate and smooth. For example, we recovered the angle of the ramp with a precision of 1deg. Finally, we compared our results with the standard EKF with *inverse depth* parametrization. A sample of the result is given by fig. 2 (bottom right): the result is not so precise compared to the SAM algorithm. Moreover, we noticed that the 99% confidence ellipses provided by the EKF are smaller thant the ones provided by the SAM algorithm. This last observation tends to show that the SAM algorithm is more consistent than the EKF (which is too optimistic).

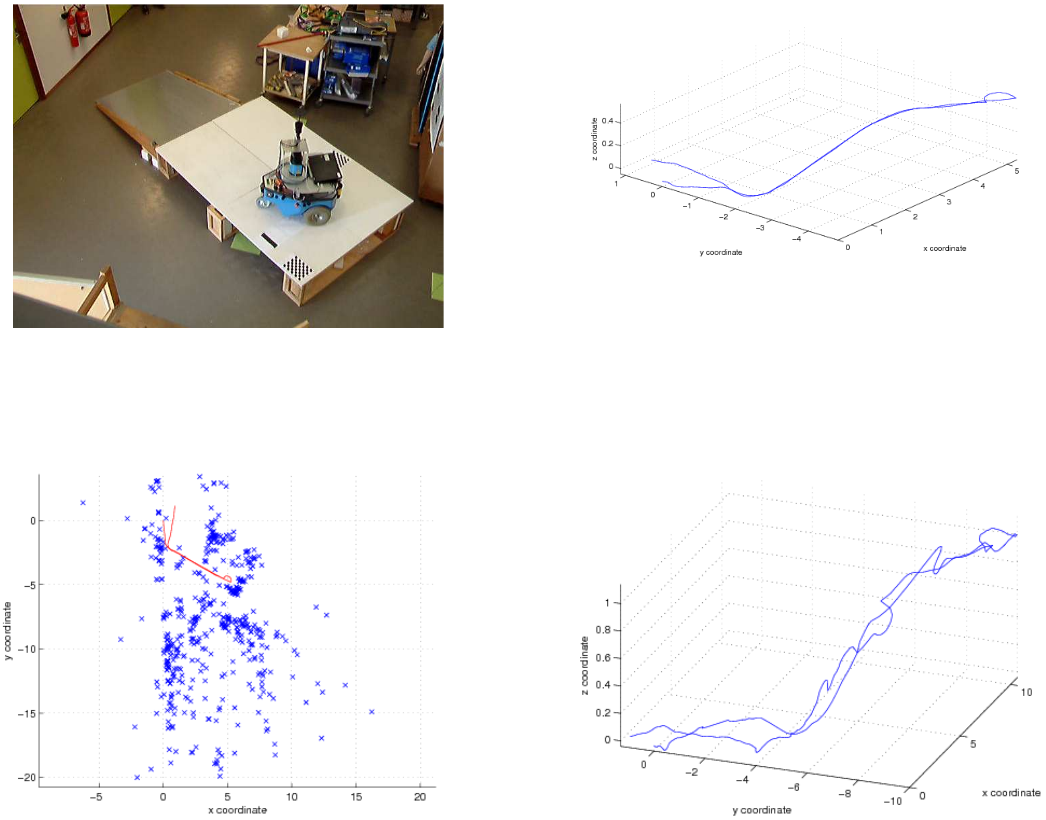

Figure 2. Results of the 6dof SAM algorithm — Top left: The inclined plane used in the experiment – Top right: 3D trajectory – Bottom left: 2D projection of the map and robot trajectory – Bottom right: 3D trajectory provided by the standard EKF algorithm

6.2.1.2. Multisensors SLAM merging catadioptric images and laser scans:

We propose an hybrid approach combining the advantages of a laser range finder and an omnidirectional camera to efficiently solve the indoor SLAM problem and reconstruct a 3D representation of the environment. We report the results validating our methodology using a mobile robot equipped with a 2D laser range finder and an omnidirectional camera.

In order to build 2D local maps of the environment we implemented an adaptation of Diosi and Kleeman Polar Scan Matching (PSM) algorithm. It directly works in the laser scanner's polar coordinate system and, therefore, does not require a time consuming search for corresponding points. Local maps are used in both the localization process and the mapping of the environment. Thanks to a SLAM approach, local maps are fused in a 2D global map and the localization of the robot is refined. Figure 3 shows the robot trajectory as computed from the wheels encoders (in red) and as computed by the SLAM algorithm (in green) superimposed on the estimated global map. The sequence was obtained by manually driving the robot to explore the ground floor of a building. Note that although we did not compensate the drift by a loop closure detection, the results are quite satisfactory. The localization obtained using the SLAM approach notably improves the dead-reckoning method based on the odometry only.

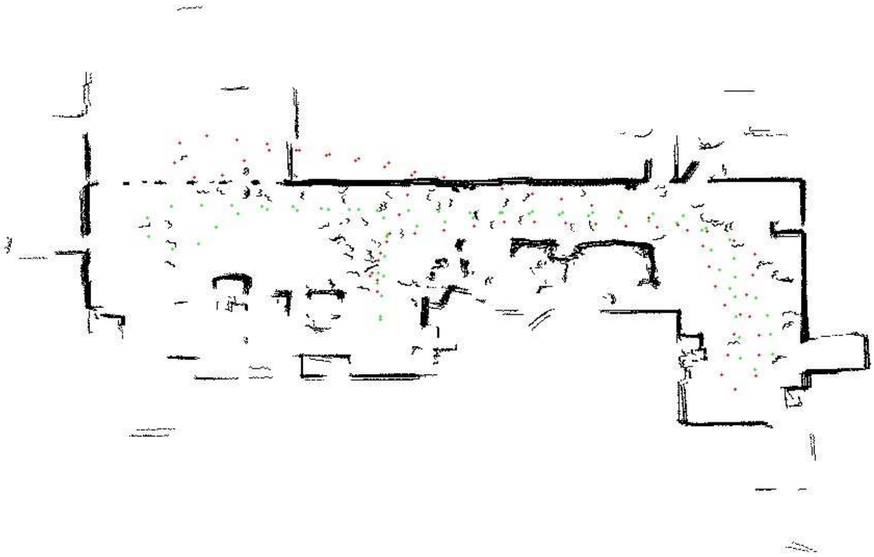

Figure 3. Laser-based SLAM

We then developed a new approach to merge laser and vision data in a consistent representation. Radial lines corresponding to approximatively vertical features (e.g. walls, facades, doors, windows) in the scene are extracted from the omnidirectional images using a Canny edge detector combined with a Hough method. As shown in Figure 4.a , by projecting the laser scan data in the omnidirectional image we can find the laser range measurements corresponding to the radial lines and, thus, compute the related 3D lines in the scene (Figure 4.b).

6.2.2. Autonomous navigation in urban environment

In order to navigate safely and autonomously in complex urban environments, it is necessary to localize the vehicle precisely in real time. Our approach is based on a novel representation, the 3D image memory, which is built during a learning step. This memory is called *Robot-centred spherical representation* and it contains a sequence of key spherical images geo-referenced in a GIS (Geographic information system). To each pixel of the sphere is associated several attributes: luminance, depth and salliency informations . This representation is generic, so that different kinds of sensors or prior knowledge on the environment can be used in the building step. In order to exploit this representation in real time during the in-line step, we define for each sphere a binary mask which allows to select only useful information for navigation. This selection step is made off-line by computing the Jacobian of the spherical image projection. Pixels that render the Jacobian matrix best conditionned allow to generate the binary selection mask (Figure 5).

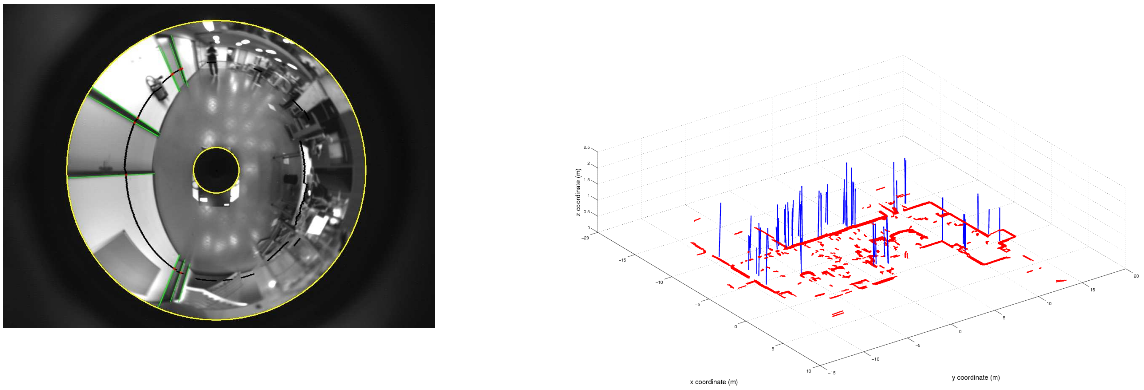

Figure 4. Fusion between catadioptric images and laser scans

During the in-line step, the current vehicle position is estimated by a direct method [2] which minimizes grey levels between the closest reference sphere and the current image. A robust estimation technique is used to reject outliers not corresponding to the objective function. The current estimated error is used to control the vehicle on a desired trajectory.

During the learning phase some parts of the world will be missing because of moving objects and limits of the sensors. The last step is to update this missing information in the database by using a SLAM technique. This step is computed in-line, so that at each new estimation the model is improved with the effect of rendering the navigation more accurate and robust.

6.3. Advanced perception : Applications

Participants: Ezio Malis, Patrick Rives, Pascal Morin, Tiago Ferreira Goncalves, Melaine Gautier, José Raul Azinheira [Univ. of Lisboa].

6.3.1. Visual servoing applied to aircraft automatic landing

Within the FP6 STReP European Project PEGASE, we were in charge of the development of a all-weather vision-based navigation aid system for the automatic approach and landing of fixed-wing aircraft. The interest for vision-based systems in aeronautics stems from the lack of alternatives to the standard ground-based instrument approach systems, like the ILS and the MLS, since the required onboard equipment is still not cost-effective for most general aviation. In addition, recent advances in terms of onboard infrared and millimetric-wave imagery sensors have improved the capability for pilots to execute non-precise approaches in all weather conditions. The objective of the developed work is thus to take advantage of these emergent imagery sensors in order to provide approach and automatic landing capabilities to the general aviation [37].

The methods previously proposed in the literature rely essentially on geometric visual features like the side lines of the landing runway and the corresponding vanishing point with the drawback that the detection of these features only occurs for the last hundred meters of the approach. In order to cope with the absence of such geometric features at higher altitudes, we have proposed to track the region around the airport using the ESM dense visual tracker, by assuming the region-of-interest (ROI) as a planar, or quasi-planar, scene. The estimated pose of the aircraft with respect to the runway can thus be retrieved from the planar homography transformation between the current image of the onboard camera and georeferenced images, previously acquired during a learning flight. Here, the database of georeferenced images was chosen to be a set of equidistant images along the reference path mostly for two reasons: the low descent angle, typically -3°, which excludes the use of

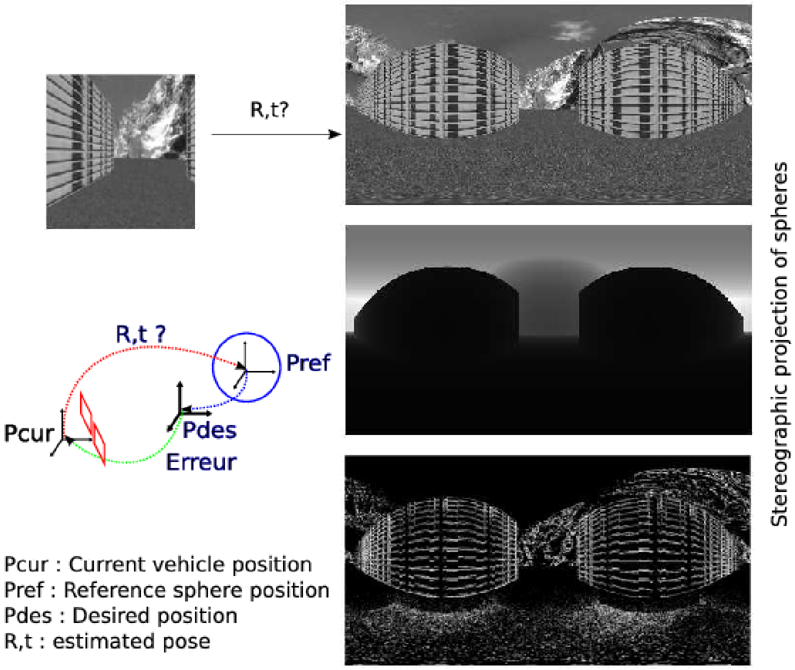

Figure 5. Autonomous navigation in urban environment

georeferenced images acquired from the nadir direction, because of the important transformation required to match both images; but also the need for path planning in the image-based visual servoing (IBVS) scheme, for the aircraft to follow a pre-defined Cartesian trajectory. To avoid that the tracked region of the image leaves the camera's field-of-view (FOV) during positioning corrections, a dynamic management of ROI was also implemented and counterbalance a possible lack of texture in the image (blue sky and sea).

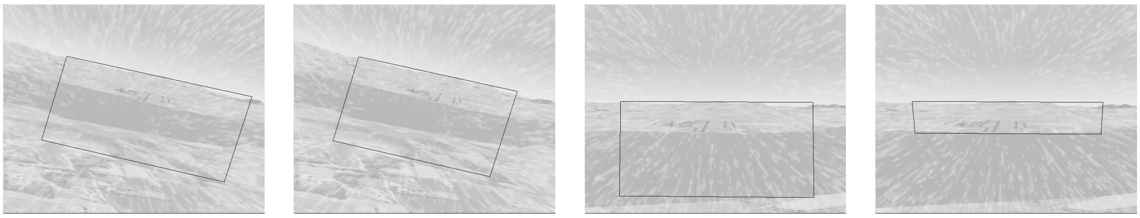

Figure 6. Dynamic management of ROIs under heavy rain: a) and b) the resize of the ROI to avoid that it goes out of FOV; and c) and d) the resize of the ROI selecting a well textured region of the image.

Concerning visual servoing algorithms the two usual control schemes were considered. In both cases, the reference trajectory is sampled with a set of images which constitutes successive desired inputs. For the position-based visual servoing (PBVS) scheme, the control objective is stated as a trajectory tracking problem in SE3. The position error is then computed from the decomposition of the homography between the current and the desired images. For the image-based visual servoing (IBVS) scheme, the control objective is stated as a trajectory tracking expressed in the SL3 homography set. The feedback error is directly built from the homography without any decomposition.

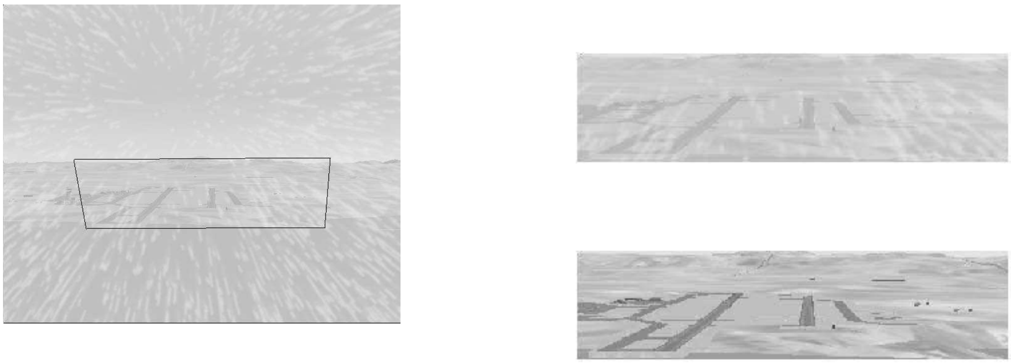

Figure 7. Visual tracking of the region around the Marseille Marignane Airport under rain and fog. The tracked ROI (left) corresponds to the patch (upper right) warped in order to match the template (bottom right).

Finally, we have proposed a modern design control technique based on the Linear Quadratic Regulator (LQR) will full state feedback, where the linearized model of the case-study aircraft was considered. In order to minimize the inherent coupling between dutch roll and roll modes, a lateral controller with two closed-loops was implemented. The inner-loop is based on an eigenstructure assignment technique that allows to assign not only the eigenvalues of the closed-loop dynamics but also the desired uncoupled eigenvectors. The outer-loop, based on the LQR, is thus in charge of the heading and lateral error control using a bank-to-turn approach.

6.3.2. Vehicle platooning :

The *Tarot* project addresses autonomy issues for military ground vehicles with a peculiar emphasis on platooning applications. A classical scenario is a convoy of vehicles going across a dangerous area (i.e. minefield) where each vehicle has to track the trajectory of the vehicle ahead perfectly. Such a task can be formulated as a visual tracking task and implemented using the ESM visual tracker presented above. First experiments have been carried out on the unmanned vehicle developped by Thalès equiped with a Pan-and-tilt unit (figure 8).

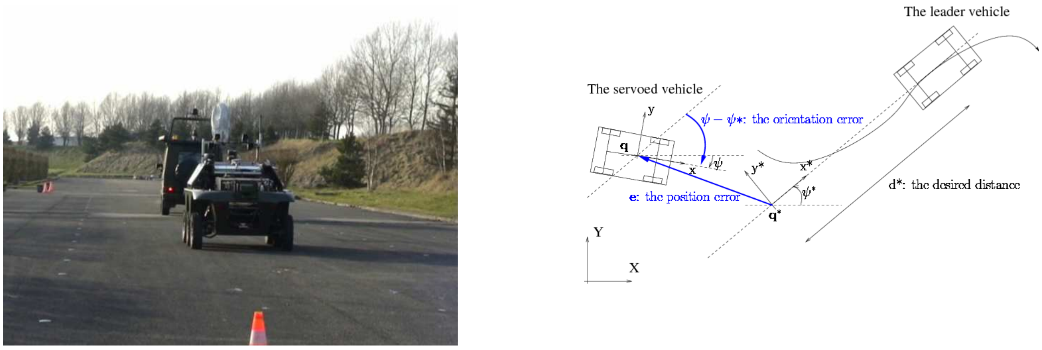

Figure 8. Platooning Task

6.3.3. Pedestrian tracking :

The aim of the *Love* project is to detect and track pedestrians seen by a camera mounted on a car. The trajectory of the pedestrian with respect to the car is estimated in order to decide wether the pedestrian may collide with the vehicle. We have used the ESM visual tracker presented above to estimate the pedestrian's motion . The experiments show that the tracker performs well when the aspect of the pedestrian does not change too much. We are currently addressing the tracking problem despite strong changes of the pedestrian's aspect and temporary occlusions.

6.4. Stabilization of mobile robots and of nonlinear systems

Participants: Claude Samson, Pascal Morin, Minh-Duc Hua, Tarek Hamel [Univ. of Nice-Sophia Antipolis], Masato Ishikawa [Univ. of Kyoto].

6.4.1. Control of snake-like wheeled robots

We are pursuing the development of the Transverse Function (TF) approach for the control of highly nonlinear systems. In relation to this endeavour, the study of snake-like wheeled robots gives us the opportunity to i) apply and adapt this approach to various mechanical systems for which no feedback control solution existed so far, ii) prolong and generalize the control design methodology associated with it, and iii) propose new paradigms for the control of systems whose motion capabilities are based on the generation of oscillatory (or undulatory) shape changes.

The idea of studying biological systems via the study of man-made robotic ersatz is not new. Nor is the mirror concept of bio-observation-inspiration invoked as an effective way to address difficult problems for which no solid theoretical corpus is yet available. For instance, a significant research effort, started many years ago, is devoted to the control of anthropomorphic and animal-like robots in order to better understand legged locomotion. Crawling locomotion, as examplified and perfected in Nature by snakes, is another complex locomotion mode which, despite decades of scrutiny by different scientific communities, still retains many mysteries. Of particular interest to us is the control of snake-like wheeled mechanisms, proposed by various researchers to better understand crawling locomotion (starting with the pioneering works of Hirose et al. [53] [52]). Indeed, most of the studies devoted to this theme have focused on the generation of open-loop control strategies yielding simple overall displacements along specified (and specific) directions, whereas attempts to synthesize feedback control laws are few, incomplete and (to our point of view) mostly inconclusive due to the non-existence of adequate control design tools. One of our objectives is to show that the TF approach, and its extensions, provide such tools.

The first mechanism of this kind that we have considered (see last year's report) is the so-called **trident snake** system depicted on Figure 9, originally proposed by Ishikawa from the University of Kyoto [56]. This is a mobile robot with a "parallel" mechanical structure, composed of a triangular-shaped body and three rotary articulations. Given a frame attached to the body, we have derived feedback control laws which ensure the "practical" stabilization of any reference trajectory for this frame, with the complementary property of maintaining the articulation angles $\phi_{1,2,3}$ away from values for which the system is kinematically singular. We have validated these controls in simulation, and Ishikawa and his students are currently working on their implementation on physical prototypes. The specific structure of the Control Lie Algebra associated with the kinematic equations of this system also gave us the idea to look for new transverse functions which differ from those that we proposed previously in that they are defined on the rotation group $SO(3)$ rather than on the three-dimensional torus $T3$. The better performance observed in simulation when using these new functions comes from the fact that they better respect the system's symmetries. We have subsequently generalized the construction of such functions on $SO(n)$ in relation to the case of a control distribution maximally generated by Lie brackets of order less or equal to two (see next subsection for more details). These results have been published in conference articles [26] [29].

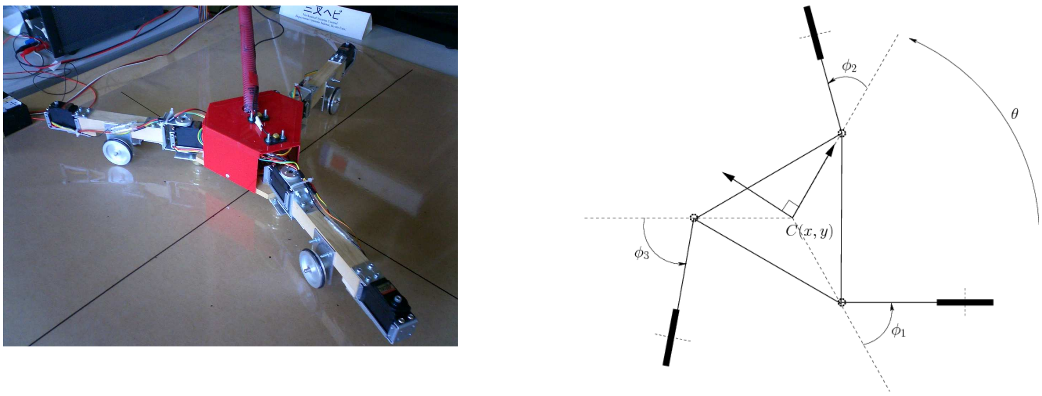

Figure 9. Trident snake

Another snake-like wheeled robot which attracted our attention this year is Hirose's **ACM III snake robot**, and more specifically the simplified model composed of three segments studied by Ostrowski and Burdick [69], depicted on Figure 10. In fact, one can distinguish several options as for the actuation of this system. The one considered by these authors corresponds to the most general case for modeling purposes. It involves five control inputs, namely two articulation angular velocities $\dot{\psi}_{1,3}$ and three “wheel” angular velocities $\dot{\phi}_{1,2,3}$. From the control viewpoint, the more the control inputs, the easier the control problem. A significantly more difficult situation is when all three wheel angles are fixed, so that only the two articulation angular velocities $\dot{\psi}_{1,3}$ can be modified. This latter case has, for instance, been considered by Ishikawa [57] to illustrate the possibility of switching between a set of piecewise sinusoidal inputs to produce a desired net displacement effect. The increased difficulty –in terms of control– also shows up in the way the Control Lie Algebra is generated. In the five-inputs case, Lie brackets of length up to two are sufficient to nominally satisfy the Lie Algebra Rank Condition for local controllability, whereas one has to go to the length three to obtain the same with only two inputs. As in the case of the trident snake, it is also important to pay attention to mechanical singularities and work out control laws which allow the system to move along any direction while ensuring that singularities are never encountered. Now, independently of the control inputs selection, one of the characteristics of this type of mechanism is that the instantaneous pose (position + orientation) velocity of any of the segments is a function of solely the system’s “shape” variables (articulations and wheel angles) and their velocities. In this respect they are alike classical nonholonomic car-like vehicles, with or without trailers, and also alike the trident snake mechanism evoked previously, whose motion can be modeled in the form of driftless control systems with velocity inputs as control variables. In the specialized literature, such systems are sometimes described as purely kinematic systems, by contrast to other systems for which complementary dynamic constraints cannot be eliminated when modeling the system’s motion. To distinguish between these two types of systems, one can also refer to purely nonholonomic systems on the one hand, and underactuated systems on the other hand. Although the TF approach has been developed for the first set of (driftless) systems originally, we have also worked on extensions of the approach to systems belonging to the second set (such as the underactuated rigid body in both planar and spatial cases).

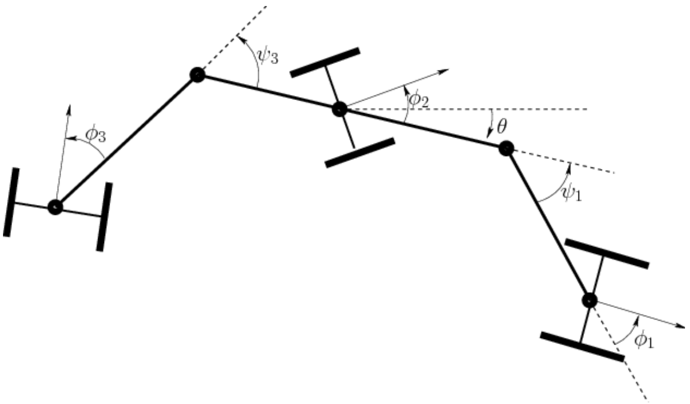

Figure 10. Kinematic wheeled-snake

The simplified **snakeboard** model (depicted on Figure 11) is a third type of wheeled snake-like mechanism whose modeling equations are used in [69] to illustrate the case of an underactuated undulatory mechanical system. Finding out how to apply the TF approach to design feedback control laws for this system gives us the opportunity to prolong our research program devoted to the extension of the TF approach to non-driftless systems and, at the same time, participate in the multidisciplinary research devoted to the comprehension of undulatory locomotion and its control.

The studies evoked above about the control of various wheeled snake-like robots in relation to the development of the TF approach have progressed well, each of them yielding solutions to previously unsolved problems. It remains to finalize them and report them in articles, the first of which will be submitted for publication during next year’s first quarter.

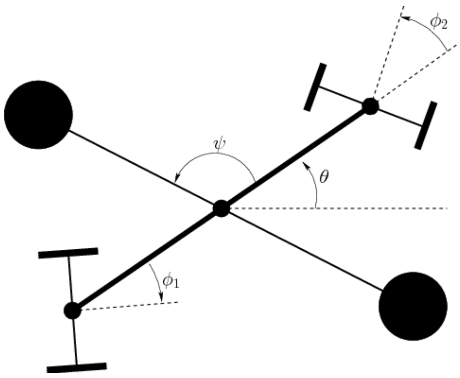

Figure 11. Snakeboard

6.4.2. Transverse functions on special orthogonal groups

The transverse function (TF) approach relies on a theorem, first proved in [9], that establishes the equivalence between the two following properties: *i)* a family of smooth vector fields satisfies the Lie Algebra Rank Condition (LARC) at a point, *ii)* there exist smooth functions, defined on a torus of adequate dimension, which are transverse to this family of vector fields. The design of such “transverse functions” is an important issue because, when applying the TF approach to the control of a system, the behavior of the controlled system strongly depends on the choice of the transverse function itself. Accordingly, in the last few years we have conducted several studies in order to design transverse functions that allow to achieve some desirable properties (like e.g. the asymptotic stabilization of feasible trajectories [11], [23]). In all these studies transverse functions were defined on a torus, as suggested by [9]. In the present study, we show that transverse functions can also be defined on other compact manifolds, like the special orthogonal groups $SO(m)$. More precisely, given a family of smooth vector fields defined on a m-dimensional manifold M, we show that the two following conditions are equivalent: *i)* these vector fields satisfy the LARC at the order one at some point p (i.e. the vector fields together with their first-order Lie brackets span the tangent space of M at p), *ii)* there exist smooth functions defined on $SO(m)$, transverse to these vector fields. From a practical point of view, these new functions have been instrumental in controlling several mechanisms like the rolling sphere or snake-like nonholonomic mechanisms (See Section 6.4.1 above). From a theoretical point of view, this result opens the door to new research investigations concerning the characterization of manifolds that can be used as definition domains of transverse functions. The results of this study are reported in the paper [29], presented at the IEEE Conference on Decision and Control (CDC).

6.4.3. Control and attitude estimation of aerial vehicles

We have continued our work on the control and attitude estimation of aerial vehicles. We are more specifically interested in small VTOL (Vertical Take-Off and Landing) vehicles which raise several difficulties from a control and attitude estimation point of view, due to a combination of factors: high sensitivity to wind gusts (which can provoke important accelerations in both position and orientation), limited actuation power compared to the intensity of aerodynamic effects, use of low cost/low weight sensors which do not provide high quality measurements, low signal-to-noise ratio of (raw) GPS absolute position measurements in the case of (quasi) stationnary flight. From a feedback control point of view, we have complemented our study recently published in the IEEE Transactions on Automatic Control [22] by addressing the combined stabilization of the vehicle’s horizontal linear velocity and altitude. This corresponds to a typical teleoperated control mode for aerial vehicles, with the linear horizontal velocity being measured by GPS or pitot-tubes, and the altitude by a barometer. This result is reported in the memoire of Minh-Duc Hua’s Ph.D. thesis [21]. We have also continued the work initiated last year on the attitude estimation problem. Attitude estimation is typically obtained by fusing GPS, magnetometers, and IMU (Inertial Measurement Unit) measurements. When the vehicle's linear acceleration is small, it is theoretically possible to reconstruct the vehicle's attitude by using only accelerometers and magnetometers measurements. To build attitude observers/filters, most existing ("classical") methods rely on this small acceleration assumption. For many VTOL vehicles however, linear accelerations may be important and induce significant errors on the attitude estimation. In a recent paper [65], Martin and Salaun have proposed a new attitude observer which uses linear velocity measurements (obtained e.g. via a GPS) in order to take into account linear accelerations in the estimation algorithm. The proposed solution shows a significant improvement with respect to classical methods when linear accelerations are not negligible. However, no analysis of the observer's stability and convergence is provided. Motivated by Martin and Salaun's result, we have worked out two new attitude observers based on linear velocity, accelerometers, and magnetometers measurements, for which we have been able to prove stability and convergence properties. The first observer establishes a property of semi-global exponential stability under a high-gain condition. For the second observer, without resorting to high-gain type arguments we show that for any initial condition of the estimator outside a set of zero measure, the estimation errors converge to zero. We also show that the set of "bad" initial conditions (i.e. those for which convergence of the estimation errors cannot be granted) is unstable. Furthermore, in the special case of constant accelerations of the vehicle, almost-global asymptotic stability of the observer is achieved. This is the strongest possible result knowing that there does not exist smooth globally asymptotically stable observers due to the topology of $SO(3)$. Alike the solution proposed in [65], simulation results show a net improvement of the attitude estimation with respect to classical solutions when the small linear acceleration assumption does not apply. The results of this study are reported in the paper [29], presented at the IEEE Conference on Robotics and Automation (ICRA), and in a journal article accepted for publication in *Control and Engineering Practice* [54].

7. Contracts and Grants with Industry

7.1. PEA Tarot (Thales/DGA)

Participants: Patrick Rives, Ezio Malis, Melaine Gautier.

This project aims at developping vision-based functions in the context of autonomous militarian terrestrial vehicles dedicated to survey missions. Among the various issues addressed by the project, let us cite the detection and the tracking of natural or artificial landmarks, and visual platooning. Developments are currently carried out in the context of the *Programme d'Etude Amont: Tarot* funded by the *DGA (Délégation Générale de l'Armement)*. Within this program, AROBAS, jointly with the INRIA project team LAGADIC, is a subcontractor of the company Thalès.

8. Other Grants and Activities

8.1. National actions

Participants: Ezio Malis, Pascal Morin, Patrick Rives, Claude Samson, Minh-Duc Hua, Glauco Scandaroli.

8.1.1. 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.

8.1.2. *ANR Psirob SCUAV (Sensory Control of Unmanned Aerial Vehicles)*

This project concerns the control of small underactuated Aerial Vehicles with Vertical Take-Off and LandingL capabilities (systems also referred to as VTOL's). Our participation is more specifically dedicated to the development of feedback control strategies in order to stabilize the system's motion despite diverse adverse phenomena, such as modeling errors associated with the vehicle's aerodynamics or pertubations induced e.g. by wind gusts.
Our partners are I3S UNSA-CNRS (Sophia-Antipolis), IRISA/Lagadic (Rennes), CEA/LIST (Fontenay-aux-roses), Heudiasyc (Compiègne), and Bertin Technologies (Montigny-le-Bretonneux).

8.1.3. *ANR Tosa CityVIP*

This CityVIP 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. An important effort is devoted to the use of on-board vision for precise vehicle localization and for the urban environment modeling. Such a model is then used in 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)

8.1.4. *Eco-Industrie program RAPACE*

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 the feedback control of 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.

8.1.5. *Collaboration with ONERA-Toulouse*

Since the begining of this fall, P. Morin supervises the Ph.D. thesis of Henry de Plinval, young engineer at ONERA-Toulouse, on the vision-based control of helicopter drones. The thesis is co-supervised by P. Mouyon (ONERA-Toulouse).

8.2. FP6 STReP European Project Pegase

Participants: Patrick Rives, Ezio Malis, Tiago Ferreira Goncalves.

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, jointly with the INRIA project team 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), Universita di Parma (Italy), EPFL (Swiss), ETHZ (Swiss), Institut "Jozef Stefan" (Slovenie).

8.3. Joint research program INRIA/FAPESP

Participants: Patrick Rives, Ezio Malis, Pascal Morin.

The project AURORA (*Autonomous Unmanned Remote Monitoring Robotic Airship*) led by the LRV/IA/CenPRA aimed 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 carried on a PhD thesis in the AROBAS team with a funding from the national brezilian agency CAPES. This thesis was defended last year. A new collaboration project between INRIA and the CTI of Campinas has been recently submitted to pursue this collaboration and investigate new research themes.

9. Dissemination

9.1. Involvement in the scientific community

- 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: ICRA, IROS, Omnivis, MFI, RFIA.
- P. Rives has been a member of the AERES committee in charge of the evaluation of the LAAS-CNRS Laboratory.

9.2. International conferences

ARobAS members have presented their work at the following conferences:

- IEEE International Conference on Robotics and Automation (ICRA), Kobe, Japan, May 2009.
- IEEE/RSJ International Conference on Intelligent Robots Systems (IROS), St Louis, USA, October 2009,
- Workshop on Omnidirectional Vision, Camera Networks and Non-classical Camera (OMNIVIS), Kyoto, Japan, October 2009,
- IEEE Conference on Decision and Control (CDC), Shangai, China, December 2009.

9.3. National conferences

ARobAS members have presented their work at the following conferences:

- Journées Nationales de la Recherche en Robotique (JNRR), Neuvy-sur-Barangeon, Novembre 2009,
- Periodic meetings of work groups of the CNRS Research Program (GDR) in Robotics.
- Simpósio Brasileiro de Automação Inteligente, Brasília, Brazil, September 2009.

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 “61^{e} Commission de Spécialistes” of the University of Nice - Sophia Antipolis.
- P. Morin is a member of the "Commission des Utilisateurs des Moyens Informatiques de Recherche" (CUMIR) at INRIA Sophia-Antipolis.

9.5. Education Through Research

- *Ph.D. Graduates* :
  - M.D. Hua, Thesis title: “Contributions au contrôle automatique de véhicules aériens ”, Université de Nice-Sophia-Antipolis, December 2009, supervisors : P. Morin, T. Hamel, C. Samson.
- *Current Ph.D. Students* :
  - A. Chapoulie, “Navigation visuelle à grande échelle en milieu urbain”, Université de Nice-Sophia Antipolis, supervisor : P. Rives.
  - T. Ferreira-Goncalves, “Contrôle d’un aéronef par asservissement visuel”, Université de Nice-Sophia Antipolis, Universidade Tecnica de Lisboa, supervisors : P. Rives, J.R. Azineira (IST Lisboa).

  - G. Gallegos, “Exploration et navigation autonome dans un environnement inconnu”, Ecole des Mines de Paris, supervisor : P. Rives.
  - C. Joly, “Contribution aux méthodes de localisation et de cartographie simultanées pour la navigation en robotique”, Ecole des Mines de Paris, supervisor : P. Rives.
  - H. de Plinval, “Commande référencée vision pour drones hélicoptères”, Ecole doctorale de Toulouse, supervisors : P. Morin, P. Mouyon (ONERA).
  - A. Salazar, “SLAM en environnement extérieur dynamique”, Ecole des Mines de Paris, supervisor : E. Malis.
  - 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, supervisor : P. Morin.
- *Participation in Ph.D. and H.D.R committees* :
  - P. Rives has participated in 5 Phd and 1 HDR defense juries.
  - C. Samson has participated in one Phd defense jury.
  - P. Morin has participated in one Phd defense jury.
- *Training periods* :
  - A. Chapoulie, “Développement d’un véhicule autonome en environnement urbain ”, 6 months, supervisor : P. Rives.
  - R. Desouche, “Fusion de données inertielles et de vision pour l’estimation de poses”, 5 months, supervisors : P. Morin, E. Malis.

9.6. Teaching

- Course on linear control at the Ecole Polytechnique Universitaire of Nice (EPU), (P. Morin, 27 hours Eq. TD).

10. Bibliography

Major publications by the team in recent years

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[21] M.-D. HUA. *Contributions au contrôle automatique de véhicules aériens*, Université de Nice-Sophia-Antipolis, December 2009, Ph. D. Thesis.

Articles in International Peer-Reviewed Journal

[22] M.-D. HUA, T. HAMEL, P. MORIN, C. SAMSON. *A control approach for thrust-propelled underactuated vehicles and its application to VTOL drones*, in "IEEE Trans. on Automatic Control", vol. 54, n^{o} 8, 2009, p. 1837-1853.

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