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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

The start-up *RoboCortex* founded by Ezio Malis, who left the ARobAS team last year, was officialy created in November 2010. *RoboCortex* markets the ESM tracking and Control Software, originally developped within ARobAS.

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

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 [44], [65] 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 [51]. 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 [66] or a single camera [39], 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 [45], or simple articulated planar objects [70].
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 [38], [48] 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 [57], [67], [73]. 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 [47] or particle filtering [46] have been proposed. More recently *undelayed* approaches [49], [54], [71] 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 [69] 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 [42], [53] 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 [37], 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 [40], [58], [64] 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 [72] 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* [41] 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 [56] 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 [55],[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 [74]. 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 (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 [60], 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 [51]. *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 [51], only partial results have been obtained in a limited number of cases [50]. 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 [59]. This study has been extended to central catadioptric cameras [61]. *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 [68], 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.

  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). 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). 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 which involves several industrial and academic partners and is managed by the french company GEOCEAN.

5. Software

5.1. Introduction

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].

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

- *HANNIBAL cart-like platform*
  Our cart-like platform, built by Neobotix, acquired two years ago to replace our previous indoor mobile robot ANIS, can operate on flat surfaces, in both indoor and outdoor environments. This platform is equiped 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 researchs in the domain of *Intelligent urban vehicle*. *CyCabs* are used as experimental testbeds in several national projects.
- *Hexacopter VTOL vehicle*

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

Figure 1. Left: The Hannibal platform. Right: The Cycab 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 Systï¿½mes) 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. The flight time autonomy varies betweem 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 equiped 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.

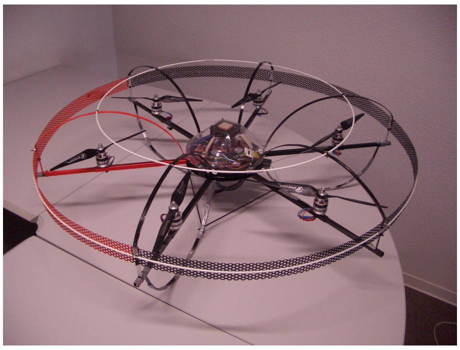

Figure 2. Hexacopter

6. New Results

6.1. Perception and autonomous navigation

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

6.1.1. Nonlinear state estimation for feedback control

6.1.1.1. Nonlinear filter design for pose estimation and online IMU calibration

This work deals with pose (i.e. position and attitude) estimation via the fusion of sensory measurements. Given pose and inertial measurements, the objective is to obtain estimates that best exploit the different measurements characteristics, while coping with measurements biases. This issue is fundamental for ground and aerial robotic applications, for which a precise knowledge of the robot location is often required. In general, high frequency measurements, typically from $50\ \mathrm{Hz}$ up to $1\ \mathrm{kHz}$, of rotational velocity and specific translational acceleration are provided by an inertial measurement unit (IMU). As a result of micro-electro-mechanical sensors (MEMS) manufacturing characteristics, IMU measurements are corrupted by additive noise and offset, also known as measurement bias. As a consequence, the estimation results obtained by using IMU data integration solely tend to drift away after a few seconds. The reduction of this drift can be achieved via a good calibration (estimation) of the sensor's bias, eventhough the time-invariant model used for the bias is only an approximation which, moreover, does not account for temperature variation effects. To this aim other sensors that provide explicit or implicit attitude and position measurements must be employed. A nonlinear observer that employs the passive complementary filter for attitude estimation, and a novel observer for position estimation and accelerometer bias calibration, have been developed. Global exponential stability of this observer is proved independently of the angular velocity. The implementation of the proposed method is simpler than Kalman-based estimators. Experimental validation of this solution using a camera for pose measurements is in progress. Furthermore, online calibration of other parameters (such as rigid transformations between different sensors' frames) is also investigated. Part of this work has been submitted for publication at the next ICRA (IEEE Conf. on Robotics and Automation). This work is also being used within the Eco-Industrie collaborative project RAPACE, and is part of Glauco Scandaroli's Ph.D. work.

6.1.1.2. Observers on the Lie group SL(3) of image homographies

A key tool in mono-camera vision and vision-based control is the Lie group SL(3), which can be associated with the set of homography matrices that relate image points of two views of a planar scene. Homographies have been used in many vision-based control schemes, for different types of robotic systems, because they implicitly contain the Euclidean information that can be retrieved from a mono-camera visual system. Several algorithms have been proposed in the past for calculation of the homography between two views of a planar scene. Understandably, these algorithms only provide in practice an imperfect estimate of the "true" homography. Furthermore, for visual-servoing applications which require high-rate real-time estimates, algorithms based on optimization methods may fail to provide accurate enough results. For all these reasons, it can be useful to use complementary sensors to improve the quality of the calculated homography. For example, inertial sensors constitute an interesting possibility, since their high bandwith can compensate for the relatively low bandwith of visual sensors.

In this work, gyrometer measurements, possibly complemented with velocity measurements, are used in order to improve homography estimates. Nonlinear observers with semi-global stability properties are derived. Different cases of interest in practice are considered, depending on whether velocity measurements are available or not. Under some conditions on the camera motion, these observers can also provide complementary information on the scene structure, like e.g. the normal to the observed plan. This joint work with R. Mahony (Australian National University) and E. Malis (RoboCortex) will soon be submitted for publication.

6.1.2. Simultaneous Localization And Mapping (SLAM)

6.1.2.1. 6dofs Bearing-only SLAM

Bearing-only SLAM is the classic formulation of the SLAM problem in the case of monocular vision where the range is not observable directly. The work started last year based on an omnidirectional camera was pursued. We developped an enhanced version of the *Inverse Depth Parameterization* which was firstly introduced in [43]. *Inverse Depth Parameterization* is generally used with an overparameterized Extended Kalman Filter (EKF) which can lead to inconsistencies. It has been shown that in the *Smoothing and Mapping* (SAM) formulation[2], it is possible to define a non-overparameterized state which leads to much better results than

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[2] The full trajectory is updated at each time-step (contrary to the EKF which filters only the current robot pose).

with the EKF. The approach was tested and validated with the data provided by an omnidirectional camera carried out by our indoor mobile robot. In a first experiment, the robot is driven on a ramp (3D trajectory) which points out the inconsistency of the EKF and, in opposite, the accuracy of the SAM formulation. In a second experiment, the robot is constrained to follow a planar trajectory (the estimation of the roll and pitch angles and the z coordinate should be zero). Once again, only our algorithm respected this property although no hypothesis was made concerning the trajectory (figure 3). These results were presented in the conference ICINCO'10 ([32]).

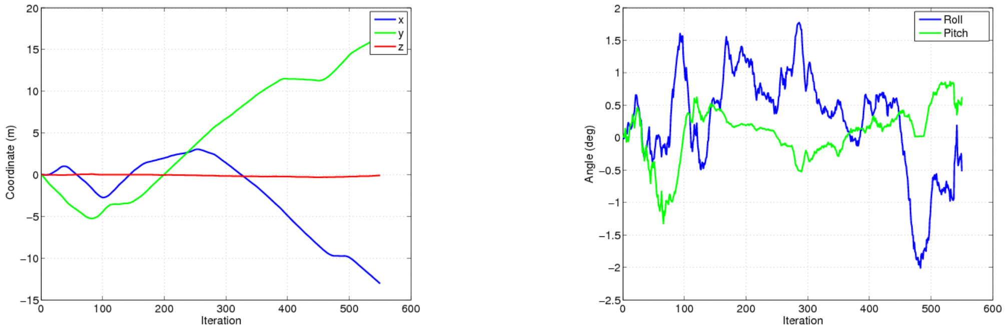

Figure 3. Results of the 6dofs visual SAM algorithm in the case of a 2D trajectory — Left: altitude estimation is very close to zero – Right: roll and pitch estimations are also very close to zero

6.1.2.2. Auto-calibration of the camera with respect to the odometry for 2D trajectories

In the case of 2D trajectories, fusing visual data and odometry information to solve the SLAM problem is a well known method. The idea is to use the odometry as an input of the motion prediction equation and the visual data in the measurement equation. However, such a method implies that the system is well calibrated: the position of the camera with respect to the odometry frame has to be known. To our knowledge, there is no method to perform the calibration operation automatically. We propose to augment the state in the SAM formulation with the unknown camera parameters (with respect to the odometry frame). This method requires to adapt a few Jacobians with respect to the original SAM algorithm which assumes that these parameters are known. However, this approach can lead to instabilities or divergence if the new system is not observable. To deal with this issue, a complete observability analysis was performed. We demonstrated that the camera parameters are observable if and only if the radius of curvature of the robot's trajectory is not constant. In practice, the robot has to make several turns. Results are presented in the figure 4. The initial values for the camera parameters are set to zero. The reference values were measured by hand on the robots. It can be seen that the estimation of the camera parameters starts when the radius of curvature changes, which was the expected result. Then, the final values provided by the algorithm are very close to the reference values. Finally, the robot trajectory and the map provided were consistent. This work has been submitted to International Conference on Robotics and Automation 2011 (ICRA11).

6.1.3. Indoor SLAM relying on a hybrid laser/omnidirectional sensor

Although the SLAM problem has been solved using many different approaches, important problems, often directly linked to the used sensors, remain. Laser range finders cannot always help in evaluating the translational motion of a robot along a straight line inside a corridor without the risk of encountering observability-related difficulties. Mapping in dynamic environments is also hard using laser data only, due to 2D measurements and slow acquisition rate. On the other hand, using exclusively visual sensors introduces issues such as propagating the scale factor correctly. We develop a novel composite sensor approach that combines the information given

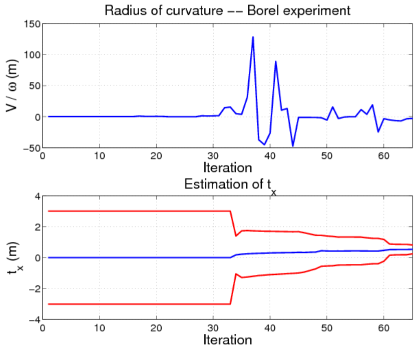

Figure 4. Estimation of the x coordinate of the camera and variation of the curvature radius of the trajectory

by an omnidirectional camera and a laser range finder to efficiently solve the indoor Simultaneous Localization and Mapping problem (SLAM). The complementarity of the sensors allows us to build a 3D representation of the environment. The planar map is obtained from the laser scans using an Enhanced Polar Scan Matching algorithm which is a generalization of Diosi's PSM algorithm. The vertical lines in the 3D scene are estimated using the radial lines extracted from the omnidirectional images. Finally, thanks to the generic projection model of the omnidirectional camera and the depth information provided by the laser range finder, we are able to build a basic wire frame 3D representation of the environment in a global coordinate system. This work [30] was published in the IEEE International Conference on Robotics and Automation (ICRA2010), held in Anchorage, Alaska from May 3 - 8, 2010.

The results above were extended in a second conference paper [29] published in the IEEE International Conference on Intelligent Robots and Systems (IROS 2010) held in Taipei, Taiwan from October 18-22, 2010. We proposed an efficient hybrid laser/vision appearance-based SLAM approach providing a reliable 3D odometry robust to illumination changes and in the presence of occluding and moving objects. The robot trajectory is correctly estimated and the drift is minimized. Furthermore, a 3D textured representation of the environment with a good resolution was obtained. Figure 5 shows the 3D textured reconstruction of the robotic hall corresponding to the merge of about 3,300 images an laser scans correctly synchronized [3].

6.1.4. Outdoor Visual SLAM

In order to navigate safely and autonomously in complex urban environments, it is necessary to have a precise localization of the robot. Classical methods, such as odometry, typically performed by wheel encoders or inertial sensors, is prone to drift and not suitable for large environments. Low cost GPS stations are inaccurate and satellite masking effect happens too frequently in urban environments to obtain a reliable localization.

Our approach consist in a vision based system associated with a database of spherical images acquired during an offline phase, which permits to obtain a robust *drift free* localization.

Basically, the database is constituted of spherical images augmented by depth and geo-located in a GIS (Geographic Information System). This spherical robot centered representation accurately represents all necessary information for vision based navigation. Furthermore, this model is generic, which means that any kind of camera sensor can be registered on it. During online navigation, the current vehicle position is obtained by comparing 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 (figure6 Left). This system is composed of six wide angle stereo cameras in overlap, which permits to extract depth

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[3] Videos of the results can be visualized at:https://www-sop.inria.fr/arobas/videos/HybridLaserOmni_IROS10.mp4

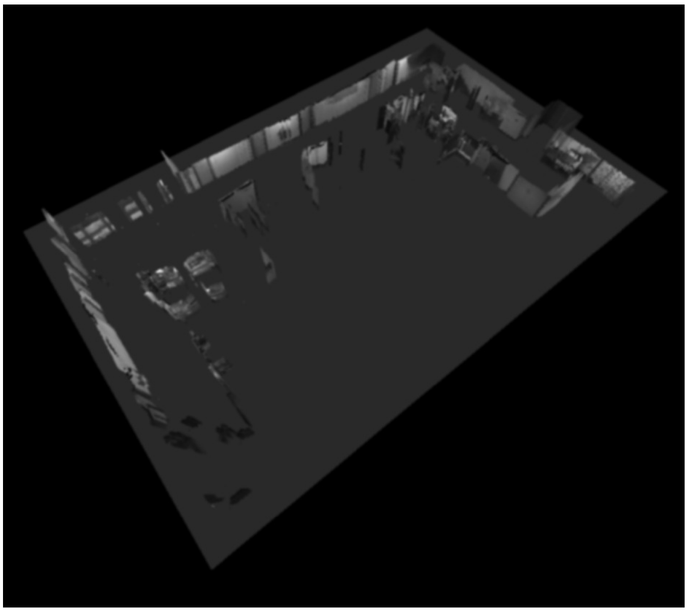

Figure 5. 3D reconstruction.

information by dense correspondence. Since the depth dimension is available, we are able to construct 360 degrees spherical images with a unique center of projection (figure 6Right). Those 3D spheres are then used in an image-based spherical odometry algorithm to obtain the vehicle's trajectory (a result submitted to the International Conference on Robotics and Automation 2011 (ICRA11)), 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, derived from [26]. This method uses all image information to compute the registration which leads to a robust and accurate localization, but since the images are in high resolution, the computational cost can be too important for real-time application. To solve this we have proposed an efficient information selection based on geometric and luminance information, which allows to speed up the registration algorithm [33] without degrading localization accuracy.

6.1.5. Loop closure detection for spherical view based SLAM

One of the major problems in SLAM is to solve the loop closure issue, a robot should be able to determine if the place it is visiting has already been visited; in a metric approach, it allows error reduction with retro-propagation and in a topological approach, it allows the graph construction and the self-localization in the environment. This year, we started a new research axis which aims at extending a loop closure algorithm previously done by Angeli Adrien and Filliat David (co-advisor of A. Chapoulie's Thesis). This algorithm performs well when the place is visited in the same direction as previously (same point of view), an example could be the detection of a loop around buildings. We extend this approach to the case of spherical views in order to allow for loop closure detection independently from the direction (different points of view). This takes advantage of a plain 360°view of the environment, essential feature for a topological multi point of view loop closure detection and map construction algorithm. Further work will focus on a real-time version of the algorithm and an improved accuracy of the loop closure detection.

Figure 6. Left: Spherical system mounted on a Cycab robot. Right:Spherical image

6.2. Control of mobile robots

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

6.2.1. Control of two-steering-wheels mobile robots with the Transverse Function approach

This study is about the control of ground vehicles with independent front and rear steering wheels. At the kinematical level, this system has three independent control inputs, namely the vehicle's longitudinal velocity along the direction joining the steering wheels axles and the front and rear steering-wheels angular velocities $\dot{\phi}_{1,2}$ (see figure 7).

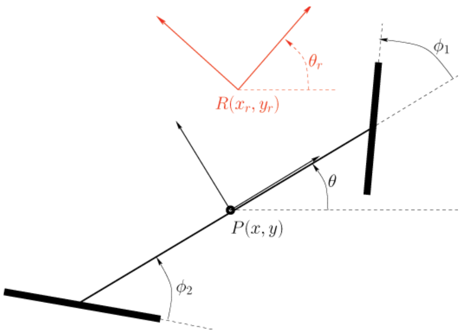

Figure 7. Two-steering-wheels vehicle. View from above

With respect to classical car-like vehicles with a single steering train, this type of vehicle provides superior maneuvering capabilities and the possibility of orienting the main vehicle's body independently of the translational motion direction. This can be used, for instance, to transport large payloads without changing the payload's orientation with respect to a fixed frame in order to minimize energy consumption. From the control viewpoint, assuming that classical *rolling-without-slipping* nonholonomic constraints are satisfied at the wheel/ground contact level, the kinematical equations of this type of vehicle yield a locally controllable five-dimensional nonholonomic (driftless) system with $SE(2) \times S^1 \times S^1$ as its configuration space. A complementary constraint, here imposed, is that singular mechanical configurations when either one of the wheel angles ϕ_1 and ϕ_2 is equal to $\pm\pi/2$ must be avoided whatever the desired gross displacement of the vehicle in the plane. This implies that certain reference trajectories in the $SE(2)$ can be stabilized only "practically" by making maneuvers, just as in the case of a car accomplishing sideways lateral displacements. The Transverse Function approach applies to this system whose structure is close to the one of a car with two control inputs in the sense that it is also locally equivalent to a homogeneous (nilpotent) system invariant on a Lie group. However, its Lie Algebra is generated differently due to the third control input. In particular, only Lie brackets of the control vector fields up to the order one are needed to satisfy the Lie Algebra Rank Condition (LARC) –the local controllability condition– at any point, whereas Lie brackets of order two are necessary in the car case. This property reflects the symmetric steering action of the front and rear wheels on the vehicle, and it is of practical importance. In order to respect this symmetry, one is led to consider transverse functions defined on the three-dimensional special orthogonal group $SO(3)$, rather than on the two-dimensional torus –a solution used in the car case, for instance. Therefore, after the trident snake studied in [52], and the rolling sphere studied in [63], this is another example of a mechanical system for which the use of transverse functions defined on $SO(3)$ is natural. As a matter of fact, this example presents the complementary interest, and complication, of involving transverse functions defined on a manifold whose dimension, equal to three, is not minimal. The corresponding extra degree of freedom thus has to be taken into account at the control design level and, if possible, be used effectively. For instance, a desirable feature is to ensure the asymptotic stabilization of *feasible* trajectories for which more classical control solutions, such as those proposed in [62], apply. In the end one obtains a unique feedback control law which ensures the avoidance of mechanical singularities, the *practical* stabilization of *any* (feasible or non-feasible) trajectory in $SE(2)$, including fixed points, and the *asymptotic* stabilization of feasible trajectories for which this objective is achievable by using classical feedback control techniques –typically when adequate conditions of *persistent excitation* upon the reference longitudinal velocity are satisfied. The results of this study will soon be submitted for presentation at an international conference. This system will also be used as an illustrating example in a journal paper adressing the construction of transverse functions on special orthogonal groups.

6.2.2. Development of an automated shopping cart

An "Action d'Envergure Nationale" (AEN) called "PAL" (for Personnal Assistant Living) has been initiated this year. This AEN regroups INRIA robotics teams with the aim of developing robotic devices that can assist elderly and disabled people in their everyday life. The AROBAS team takes part in this AEN through the development of an automatic shopping cart. The subject involves feedback control of nonholonomic systems, pose reconstruction via vision sensors, and obstacle avoidance in dynamic environments. Luca Marchetti has recently started a post-doc on this topic within the AROBAS team. Experiments will be conducted on the ANG walker developed by the COPRIN team.

6.2.3. Time sub-optimal nonlinear PI and PID controllers applied to longitudinal headway control

Proportional integral (PI) and proportional integral derivative (PID) controllers are at the heart of control engineering practice and, owing to their relative simplicity and satisfactory performance for a wide range of processes, have become the standard controllers used by industry. Perhaps only 5-10% of man-implemented control loops cannot be controlled by single input, single output (SISO) PI or PID controllers. However, this widespread usage also goes with numerous problems due to either poor tuning practice or limited capabilities offered by standard PI-PID schemes. These problems have in turn periodically revived the interest from the academic research community in order to work out complementary explanations and solutions.

In particular, a well-known source of degradation of performance is the occurrence of control saturation, when the boundedness of the "physical" control that can be applied to the system under consideration is no longer compatible with the application of the (theoretically unbounded) calculated control value. This has the consequence of invalidating the performance index established on the assumption of linearity of the controlled system, and can give rise to various undesired (and unnecessary) effects such as multiple bouncing between minimal and maximal values of the control, and important overshoots of the regulated error variables. The so-called integrator wind-up phenomenon, which worsens the overshoot problem and the reduction of which still motivates various research studies is also commonly presented as a consequence of control saturation combined with the integral action incorporated in the control law in order to compensate for unknown (slowly varying) additive perturbations. Compared to the already huge corpus of studies devoted to PI and PID controllers, the present study has the limited ambition of proposing new nonlinear versions of these controllers that attempt to combine the constraints of control saturation with *i)* the objective of optimizing the control action to reduce the size of initially large tracking errors as fast as possible, and *ii)* the design of integral action terms with limited wind-up effects. The former issue is close to the line of research on "proximate" time-optimal for linear systems admitting closed-form time-optimal solutions. The study is restricted to the simplest first and second order linear systems. In particular, continuous nonlinear proportional (P) and proportional derivative (PD) state feedbacks depending continuously on an extra-parameter whose convergence to infinity yields the discontinuous time-optimal controls for these systems are derived and form the cores of the PI and PID controllers proposed subsequently. As for the latter issue, it is related to the work on anti-windup and "conditional integrators". This work is also related to the theme of bounded control design based on the use of nested saturation functions with the same concern of proving *global* asymptotic stability of the desired set-point, but with a different way of designing the control solutions. In the second part of the study, the proposed nonlinear PID controller is applied to the longitudinal headway control of a car following a leader. The reason for choosing this application is its good fit with the design constraints and objectives imposed on the control and its performance, namely the existence of different bounds on the car's acceleration and deceleration capabilities, control effectiveness in terms of time of convergence to the desired inter-distance between the two vehicles, absence of bouncing transients –for the comfort of the passengers, fuel economy, and reduced wear-off of mechanical parts–, and very small overshoot in order to avoid collisions with the leader. The results of this study are reported in a paper submitted for presentation at an international conference.

6.2.4. Control of aerial vehicles subjected to lift forces

We have continued our work on 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. This is the subject on an ongoing thesis research project. We have previously studied the simplified case when environment forces acting on the vehicle do not depend on the vehicle's attitude (orientation), an idealization of which corresponds to the case when the vehicle's shape is spherical [5]. In the first approximation, this property holds for VTOL vehicles such as helicopters and small drones mostly used for their hovering capabilities at reduced velocities. It may also hold for ellipsoidal or tubular shaped rockets and marine vehicles with small external wing-shaped appendages (such as rudders mostly used to modify the vehicle's attitude). But it does not hold for airplanes the flight's basics of which heavily rely on the existence of important lift forces associated with the presence of large wings attached to the main vehicle's body. The work has this year thus focused on the modelling of such lift forces and their taking into account at the control design level. To simplify the study, we have been concentrating on the 2D case, i.e. motion in the vertical plane exclusively. In the long range, one of our ambitions is to encompass within a unified nonlinear control design framework most of the methodology based on linear control techniques on which current marine and airplane autopilots rely and, from there, improve on this methodology.

6.2.5. Vision-based control of helicopter drones

Unmaned Aerial Vehicles (UAVs) can be used for many surveillance and monitoring applications, both indoors and outdoors. Their effectiveness relies in the first place on the use of embarked sensors that can provide information on the vehicule's *pose* (i.e. position and orientation). In teleoperated modes, the human operator can compensate for the lack of some pose information (like, e.g., the vehicule's position). For fully autonomous control modes, however, information on both position and orientation is necessary. This is often a challenging problem for small VTOL UAVs (Vertical Take-Off and Landing vehicles) due to several reasons. For example, no sensor can provide a direct measure of the 3D-orientation. Also, GPS sensors that are usually used to retrieve position, do not provide precise and high-rate measurements, and these sensors are not always operational (like, e.g., urban canyons). Other sensors should be used to improve UAV's effectiveness, especially those providing information about UAV's local environment. One of the most promising alternatives is the use of vision sensors.

In this work, we address the problem of controlling VTOL UAVs' hover flight, based on measurements provided by a single camera and gyrometers only. The solution relies on the measure of the homography matrix associated with the camera's observation of a planar target. There are several challenges associated with this problem. First, since we do not assume any information on the target (like, e.g., size or inclination), the vehicle's pose cannot be extracted from the homography measure. Then, unlike previous works on the subject, we do not assume that the vehicle's orientation can be reconstructed (using, e.g., information on the target or additional sensors). Finally, we do not have any sensor that provides linear velocity measurements either. An homography-based controller is proposed, together with a complete stability and robustness analysis. A remarkable aspect of this solution is that given any lower bound on the distance between the reference hover flight position and the visual target, control gain that guarantee local asymptotic stability of this position can be designed without explicit knowledge of the associated distance. This work has been submitted for publication at the next ICRA (IEEE Conf. on Robotics and Automation), and is part of Henry de Plinval's Ph.D. work. Henry de Plinval is an engineer at ONERA, co-supervised by P. Morin and P. Mouyon (ONERA).

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. Other Grants and Activities

8.1. National Initiatives

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

Participants: Claude Samson, Tarek Hamel, Pascal Morin.

This project concerns the control of small underactuated Aerial Vehicles with Vertical Take-Off and Landing (VTOL) capabilities. 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).

8.1.2. ANR Tosa CityVIP

Participants: Patrick Rives, Andrew Comport, Maxime Meilland, Alexandre Chapoulie, Mathieu Seiler.

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 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 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)

8.1.3. Collaboration with ONERA-Toulouse

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, Tiago 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/CNPq

As a follow up to the long time collaboration between EPI ARobAS and the CTI/CenPRA 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, three members of ARobAS have spent two weeks in Campinas for working with CTI researchers. The visit of CTI researchers at INRIA 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.
- P. Rives was a member of the AERES committee in charge of the evaluation of the LAAS-CNRS Laboratory.
- P. Rives provided the Agence Nationale de la Recherche (ANR) and the Swiss National Science Foundation with expertise work.
- 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), Anchorage, Allaska, May 2010.
- International Conference on Informatics in Control, Automation and Robotics (ICINCO), Funchal, Madeira, June 2010.
- IEEE/RSJ International Conference on Intelligent Robots Systems (IROS), Taipei, Taiwan, October 2010,
- IEEE Conference on Decision and Control (CDC), Atlanta, USA, December 2010.

9.3. National conferences

ARobAS members have presented their work at the following conferences:

- Journées Nationales des Jeunes Chercheurs en Robotique (JJCR), Paris, Novembre 2009,
- Periodic meetings of work groups of the CNRS Research Program (GDR) in Robotics.

9.4. Activities of general interest

- C. Samson was a member of the “Bureau du Comité des Projets” at INRIA Sophia-Antipolis up to July 2010.
- 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* :
  - T. Goncalves, “Contrôle d’un aéronef par asservissement visuel”, Université de Nice-Sophia Antipolis, Universidade Tecnica de Lisboa, supervisors : P. Rives, J.R. Azinheira (IST Lisbon). Thesis defended on December 2.
  - C. Joly, “Contribution aux méthodes de localisation et de cartographie simultanées pour la navigation en robotique”, Ecole des Mines de Paris, supervisor : P. Rives. Thesis defended on June 30.
- *Current Ph.D. Students* :
  - A. Chapoulie, “Navigation visuelle Ã grande échelle en milieu urbain”, Université de Nice-Sophia Antipolis, supervisors : P. Rives, D. Filliat (ENSTA).
  - G. Gallegos, “Exploration et navigation autonome dans un environnement inconnu”, Ecole des Mines de Paris, supervisor : P. Rives.
  - M. Meilland, “SLAM visuel et navigation autonome en environnement urbain”, Ecole des Mines de Paris, supervisors : P. Rives, A. Comport.
  - H. de Plinval, “Commande référencée vision pour drones hélicoptères”, Ecole doctorale de Toulouse, supervisors : P. Morin, P. Mouyon (ONERA).
  - D. Pucci, “Control of thrust-propelled vehicles”, Université de Nice-Sophia Antipolis, supervisors : T. Hamel, C. Samson.

  - A. Salazar, “Direct Self-Calibration of Central Catadioptric Omnidirectional Cameras” 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 participated in six Phd defense juries.
  - C. Samson participated in one Phd defense jury at the IST-ISR, Lisbon, Portugal.
  - P. Morin participated in two Phd defense juries.
- *Training periods* :
  - M. Seiler, “Développement d’un capteur de vision sphérique pour la roboptique mobile autonome ”, 6 months, supervisor : P. Rives.
  - D. Cabecinhas, “Control of aerial vehicles”, 2,5 months, supervisor : C. Samson.

9.6. Teaching

- Course on linear control at the Ecole Polytechnique Universitaire of Nice (EPU), (P. Morin, 23 hours Eq. TD).
- Course on SLAM at the Ecole Centrale de Nantes (Master Erasmus Mundi), (P. Rives, 8h cours).
- Seminar on SLAM at Dassault Aviation (1 day, organizer and speaker).
- Lecture on the Transverse Function control approach at the IST-ISR, Lisbon, Portugal,

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Major publications by the team in recent years

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[24] C. JOLY. *Contributions aux méthodes de localisation et cartographie simultanées par vision omnidirectionnelle*, Doctorat ParisTech, June 2010.

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