INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team icare

Instrumentation, Commande et Architecture des Robots Évolués

Sophia Antipolis

THEME NUM

Activity Report

2004

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2. Overall Objectives

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

3. Scientific Foundations

3.1. Introduction

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

3.2. Robot modeling and control

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

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

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

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

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

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

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

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

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

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

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

Since robotic, or "robotizable", mechanisms are structurally nonlinear systems which, in practice, need to be controlled in an efficient and *robust* manner, the project ICARE has natural interest and activities in the domain of Automatic Control related to the theory of control of nonlinear systems. Concerning fundamental and methodological developments conducted around the world in this domain, the study of mechanical systems and their automatization –which is the core of Robotics– has played, and continues to play, a privileged role [52]. This has a historical foundation, since one can argue that Automatic Control, as an engineering science, started with the regulation of mechanical systems. Let us cite, for instance, the centrifugal regulator of Watt in the 18th century, the automated ship pilots of Minorsky in 1922, and the problems of guidance and stabilization of aerial and space devices during the Second World War. More recently, the manipulator arms have been used as a model to illustrate the interest of feedback control linearization. The studies of robustness with respect to modeling errors (arising from uncertainties about the mechanical parameters, the exteroceptive sensors' parameters, or the environment observed via the sensors) have allowed to refine the stability analyses based on Lyapunov functions and to illustrate the interest of approaches which exploit the structural passivity properties associated with hamiltonian systems. Even more recently, the study of nonholonomic mobile robots has been the starting point for the development of new approaches, such as the characterization of differential *flatness* [51], used to solve trajectory planning problems, and *time-varying feedback control* techniques [46], used to solve the problem of asymptotic stabilization of a fixed point.

In this context, the research done in the ICARE project mainly focuses on feedback control stabilization issues. In the case of the manipulator arms, it has produced the so-called *task function* approach [17] which is a general framework for addressing sensor-based control problems. As for our studies about mobile robot control [18], they have given birth to the theory of stabilization of nonlinear systems via *time-varying continuous state feedback* and, even more recently, to a new approach of *practical stabilization* [48]for "highly" nonlinear systems.

3.3. Perception

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

Participants: Ezio Malis, Patrick Rives, Vincent Benhimane, Vincent Brandou, Christopher Mei, Alessandro Corrêa-Victorino, Nicolas Simond.

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

3.3.1. Sensor modeling and fusion

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

- *Realistic sensors models :* The simple models commonly employed to describe the formation of sensor data (i.e. pinhole camera, Lambertian reflection...) may fail to accurately describe the *physical* process of sensing. Improvement in this respect is possible and useful [49], [45].
- *Sensor Fusion :* The integration of several complementary sensory information can yield more reliable constructions of models of the environment and more accurate estimations of various position/velocity-related quantities. This can be done by mixing proprioceptive and exteroceptive data. Sensor fusion is an important, still very open, domain of research which calls for more formalization.

3.3.2. Robust tracking of landmark

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

- *Outliers rejection :* Outliers, which do not correspond to anything in the physical world, have to be filtered out as much as possible. Standard Least-Squares or Kalman filtering techniques are inefficient in this respect, and they can in fact produce catastrophic results when the rate of outliers increases. Robust estimators (voting, M-estimators, Least Median Squares,...) have been specifically developed to solve this problem.
- *Parameter estimation and filtering :* Extended Kalman Filtering techniques (EKF) are commonly used in robotics to deal with noisy sensory data. However, in some cases, depending for instance on the noise distribution characteristics, the stability of such a filter can be jeopardized. An alternative consists in using *bounded-error methods* [50] whose stability is independent of the noise distribution. These techniques have been successfully applied to robot motion estimation when using a laser range finder [21].

3.3.3. Sensor-based control

Perception aspects have to be taken into account very early at the task planning level. An outcome of this planning phase is the design and selection of a set of sensor-based control loops in charge of monitoring the interaction between the robot and its environment during the task execution [14]. Another one is the specification of external events the occurrence of which signals, among other things, when the system's actions have to be modified by replacing the currently running sensor-based control by another one (reactive aspect). In both cases, it matters to use perception information so that the success of the resulting control strategy is not jeopardized when the task execution conditions are slightly modified (robustness). In ICARE, we often use the formalisms of task-functions and virtual linkages [17] for the design of such sensor-based control laws, each of them corresponding to an elementary sensor-based action (wall following, for example). These formalisms are general so that they apply to various sensors used in Robotics (odometry, force sensors, inertial navigation systems, proximetry, local vision).

3.4. Robot navigation

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

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

Many application fields (transportation, individual vehicles, aerial robots, observation underwater devices,...) involve navigation issues, especially when the main goal is to make a robotic vehicle move safely in a partially unknown environment. This is done by monitoring the interaction between the vehicle and its environment. This interaction may take different forms : actions from the robot (positioning with respect to an object, car parking maneuvers,...), reactions to events coming from the environment (obstacle avoidance,...), or a combination of actions and reactions (target tracking). The degree of autonomy and safety of the system resides in its capacity to take this interaction into account at all the task levels. At a higher level, it also requires the definition of a planning strategy for the robot actions during the navigation [47]. The spectrum of possible situations is large, ranging from the case when the knowledge about the environment is sufficient to allow for off-line planning of the task, to the case when no information is available in advance so that on-line acquisition of a model of the environment during an initial exploration phase is required [44].

The problems of navigation addressed by the ICARE team concern both indoor and outdoor environments (urban-like). The approaches that we develop are based on three ideas : i) combine the information contained in proprioceptive and exteroceptive sensory data, ii) use sensor-based control laws for robot motion and also to enforce constraints which can in turn be used for the localization of the robot and the geometrical modeling of the environment, and iii) combine locally precise metrical models of the environment with a global, more flexible, topological model in order to optimize the mapping process [21], [22].

3.4.1. Exploration and map building

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

3.4.2. Localization and guidance

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

In the same way as it is important to take perception aspects into account very early at the task planning level, it is also necessary to control the interaction between the robot and its environment during the task execution [14]. This entails the explicit use of perceptual information in the design of robust control loops (continuous aspect) and also in the detection of external events which compel to modify the system's actions (reactive aspect). In both cases it matters to robustify the system's behavior with respect to the variability of the task execution conditions. This variability may arise from measurement errors or from modeling errors associated either with the sensors or the controlled systems themselves, but it may also arise from poor knowledge of the environment and uncertainties about the way the environment changes with time. At the control level, one has to design feedback control schemes based on the perceptual information and best adapted to the task objectives. For the construction of suitable sensor-based control laws one can apply the task-function approach which allows to translate the task objectives into the regulation of an output vector-valued function to zero. Reactivity with respect to external events which modify the robot's operating conditions requires detecting these events and adapting the robot's behavior accordingly. By associating a desired logical behavior with a dedicated control law, it becomes possible to define *sensor-based elementary actions* (wall following, for instance) which can in turn be manipulated at a higher planning level while ensuring robustness at the execution level. The genericity of the formalisms suggests that they can be applied to various sensors used in Robotics (odometry, force sensors, inertial navigation systems, proximetry, local vision,...).

3.5. Means of experimentation

Experiments are currently conducted on two test-beds.

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

4. Application Domains

4.1. Panorama

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

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

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

4.2. Automatic driving

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

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

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

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

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

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

4.3. Indoor Robotics

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

Participants: Patrick Rives, Alessandro Corrêa-Victorino.

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

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

4.4. Aerial robotics

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

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

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

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

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

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

5. Software

5.1.1. Specific software for experimental purpose

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

5.1.2. Image processing

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

6. New Results

6.1. Stabilization of mobile robots and of nonlinear systems

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

Participants: Claude Samson, Pascal Morin, Guillaume Artus, Matthieu Fruchard, Mauro Maya Mendez, Teddy Alfaro.

We are interested in the stabilization of controllable nonlinear systems which lose the property of being controllable when they are linearized at an equilibrium point. Wheeled mobile robots subjected to nonholonomic contraints belong to this category of systems. In the past, we have addressed this problem via the development of the theory of time-varying feedback control. In the last few years we have focused our research on a new control approach, that we have called the *Transverse Function* approach [9][11][10], with the objective of stabilizing asymptotically a set contained in an arbitrary "small" neighborhood of the state-point of interest (a type of practical stabilization), rather than stabilizing asymptotically the point itself –as we used to do. This objective is all the more natural that the point of interest may not be stabilizable. It may also seem less ambitious than the former one —when the point of interest is stabilizable—, since the asymptotic stabilization of a point implies that this point is practically stabilized. We believe that it is in fact complementary, more general (since it encompasses all point asymptotic stabilizers), and well suited to this class of nonlinear systems. For instance, it allows to better account for what can be done to reject additive perturbations acting on the system. This contributes to the enlargement of the range of applications that can be addressed by the control solutions so derived.

6.1.1. Trajectory tracking for mobile robots with a trailer

The transverse function approach is very well suited to the design of feedback stabilizers for non-holonomic mobile robots. When the kynematic equations of the robot are left-invariant with respect to a Lie group product, as in the case of unicycle-like systems for example, this approach allows to globally stabilize any trajectory in the state space (feasible or not), with a single controller. The stabilization is ensured in a practical sense, i.e. the norm of the tracking error is ultimately bounded by a pre-defined arbitrary positive value. When the kynematic equations of the robot are not left-invariant with respect to a Lie group product (like e.g. car-like vehicles or more generally unicycles with trailers), the conditions of application of the t.f. approach need to be further evaluated. Last year, we had shown that the t.f. approach could be applied to car-like vehicles in order to globally practically stabilize any reference trajectory in $SE(2)$ (i.e. any reference trajectory associated with the posture of the robot in the cartesian space). The objective of the present work was to extend this result to unicycles and cars pulling a trailer of the "general type", i.e. with a hitching point not necessarily located on the rear-wheels' axle of the front vehicle. This setting includes in particular conventional trucks. Based on the t.f. approach, feedback laws have been designed for both systems (unicycle and car with a trailer). Similarly to the case with no trailer, they allow to globally practically stabilize, for the trailer, any reference trajectory in $SE(2)$. Simulation results have validated the property of practical stability obtained with these controllers. Future work on this problem will concern control optimization in order to improve the transient behavior, and modify the tracking precision in relation to the feasibility of the reference trajectory.

6.1.2. Stability and robustness of sensor-based controlled non-holonomic mobile robots

The motivation for the present work is the development of sensor-based control for non-holonomic systems. The system here considered is a unicycle-like robot equipped with a sensory system which provides data from which the posture of the robot with respect to a fixed reference frame can be calculated. A typical example of such a system is Icare's mobile robot ANIS, equipped with a camera observing a rigid object with which a reference frame is associated. In many applications however, both models of the sensor and of the environment are inaccurate, so that the calculation of the robot's posture with respect to the reference frame cannot be precise. The “long-term” objective of this work is to develop control methods for non-holonomic mobile robots which are robust against measurements uncertainties of this type. In the present work, we have assumed that the sensor provides an accurate value of the robot’s orientation error with respect to the reference frame. However, the position error vector is known only up to a scaling factor $\lambda > 0$. This means that the direction of the target with respect to the robot is known precisely, but its distance to the robot is not. For a video camera, this type of measurement error arises, for example, from the imprecise knowledge of the camera’s focal length or, equivalently, from uncertainties upon the target’s geometry and size. Assuming that the sensor is located on the rear wheels’ axle of the robot, we have designed feedback laws that practically stabilize the robot’s posture for any $\lambda > 0$. These control laws, derived with the transverse function approach, further guarantee that the robot’s velocity converges exponentially to zero. The set of possible asymptotic postures itself depends upon λ and the parameters of the transverse function which is used, with the distance between this set and the reference frame (which characterizes the achievable ultimate precision) being commensurate to the size of the transverse function. Simulation results suggest that these controllers are robust with respect to much more general measurement errors. However, this property needs to be investigated further, in relation to the adaptation of sensor-based control methods used for holonomic manipulator arms.

6.1.3. Control of nonholonomic mobile manipulators

Our research on this topic corresponds to our participation in a project involving two other robotics laboratories (LAAS-CNRS of Toulouse and LGP-ENI of Tarbes), within the national program ROBEA jointly supported by the CNRS and INRIA. The project’s central theme is the control of robotic mixed mechanical structures composed of a holonomic manipulator arm mounted on a nonholonomic mobile base (like cranes). In order to decouple the problems of redundancy and nonholonomy whose combination epitomizes the difficulty of controlling nonholonomic mobile manipulators, we have proposed last year the concept of “equivalent omnidirectional mobile manipulator”. The underlying idea was to conceptually associate the physical nonholonomic system with a virtual holonomic one the control of which can be addressed by using classical methods used for manipulators, such as those issued from the Task Function approach [17]. This idea seemed all the more seductive that the Transverse Function approach provides a natural way of associating a nonholonomic wheeled vehicle with an omnidirectional one in such a way that any trajectory of the latter vehicle can be tracked by the nonholonomic vehicle with predefined (arbitrary) precision. From there, it “only” remained to define the equivalent manipulator (with equivalent joint coordinates) which, mounted on the virtual omnidirectional base, would be in charge of performing the same manipulation task as the physical manipulator mounted on the nonholonomic base. The control law of the nonholonomic system could then be deduced from the one derived for the equivalent holonomic system. The technicalities associated with the actual implementation of this idea have been worked out, and extensive simulation testing (by taking into account control bounds, control discretization, and target velocity estimation) has been carried out to prepare forthcoming experiments on our mobile robot prototype ANIS. However, unforeseen difficulties were also revealed along this process, leading us to realize recently that this approach may not be as fruitful as we first anticipated because it raises severe complications related to the determination of the equivalent manipulator’s joint coordinates without being very effective for solving the important practical issue of avoiding joint limitations by using the extra degrees of freedom offered by the mobile base. For these reasons, we are now considering a somewhat simpler control design methodology, still based on the Task Function approach to formulate the manipulation task and on the Transverse Function approach to take care of the nonholonomy aspect of the problem via the minimization of a secondary cost, but without the explicit introduction of equivalent joint coordinates at the manipulator’s level. To complement our reflexion about these conceptual and methodological matters, a new campaign of simulations which will hopefully comfort us in the new direction taken up by this research has been launched.

6.1.4. Vision-based control of a unicycle-type vehicle: experimentation and complementary control aspects

The problem here considered is the tracking of a moving target, materialized in our experiments by a frame rigidly linked to three vertical bars mounted on an omnidirectional mobile basis, by a nonholonomic unicycle-type vehicle (our mobile robot ANIS, for instance) equipped with a calibrated camera which observes the three bars. The posture of the vehicle with respect to the target is calculated from the visual data and from the knowledge of the bars' geometry. Last year, a control solution based on the Transverse Function approach had been proposed and experimentally tested. This work has been taken up further this year.

Firstly, a new family of feedback laws has been proposed in order to reach a good compromise between the tracking precision and the frequency of the maneuvers which are needed to track the target in many cases. Indeed, when the motion of the target is feasible for the mobile robot, good precision (i.e. small tracking errors) can be obtained without maneuvering, whereas the tracking of non-feasible trajectories necessitates maneuvers whose frequency is (roughly) inversely proportional to the tracking precision. The aforementioned compromise is managed via the use of over-parameterized transverse functions, with the extra parameters utilized to dynamically adapt the "size" of the transverse function (and thus the tracking precision) depending on the target's motion. With this kind of transverse function, asymptotic stabilization of a fixed target can also be achieved, as shown previously in [25].

Secondly, new experiments have been conducted. They incorporate the control modifications evoked above, as well as other aspects developed last year in order to reduce the control effort during the initial transient phase (for instance, when the mobile robot is initially far from the target).

These developments and a selection of experimental results have been collected in a technical report [43] and presented at a symposium [26].

6.2. Mobile robot navigation and guidance

Keywords: *safe navigation for a mobile robot*, *sensor fusion*, *sensor-based planning and control*, *simultaneous localization and mapping (SLAM)*.

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

Autonomous navigation of a mobile robot requires basic capabilities for sensing the environment in order to avoid obstacles and move in a safe way. The literature on the problem of safe navigation shows a trend of solutions based on the coupling of path planning and motion control techniques. In the Icare team, we address the problem via the exploration and representation of an unknown indoor environment. This is the so-called simultaneous localization and mapping (SLAM) approach. The indoor mobile robot which we consider is equipped with a laser scanning device providing us with a planar cross section of the environment. Recently, we initiated a new research trend which addresses the use of omnidirectional vision to compensate for the low degree of discriminancy of the laser. The exploration method is purely reactive, in the sense that it does not rely upon a preliminary trajectory planning procedure, and it guarantees a safe navigation in the free space of the environment. Reactive sensor-based navigation tasks and closed loop control laws are derived by using information gathered while the robot moves and progresses in its workspace. The closed-loop sensor-based control is designed so as to guarantee, along the exploration process, path-following error bounds that are independent of the distance covered by the robot. A model of the environment is built, based on an initial hybrid (metric and topological) representation which is updated and further refined during the exploration of the environment. The robot is precisely localized, in a set of local metric maps, when arriving in the vicinity of known predefined locations and objects in the environment. When it navigates between two such places, a topological description of the environment still provides a coarse localization.

A second research direction is devoted to the problem of autonomous navigation in an urban environment. In this case robust localization is a critical issue. During the last decade, the DGPS has become the most used technology for localization in outdoor environments. However, the localization quality depends on the number of satellites "visible" by the antenna. High buildings and trees reduce the signal-to-noise ratio by obstructing the view and creating multiple paths which corrupt the data. Moreover, the resolution available with such a system is about one meter in the best case. This is not sufficient in front of the ten centimeters precision which is required. Concurrently, recent progress in computer vision resulting from the reduction of data processing times now allows the vision sensor(s) to be used as the main localization system in association with a DGPS-based system. In this respect, we are developing a vision-based approach to estimate the vehicle displacements by using an on-board weakly calibrated stereovision system.

6.2.1. Simultaneous Localization and Mapping (SLAM) in unknown indoor environments

After more than two decades of intense research the SLAM (*Simultaneous Localization And Mapping*) problem remains largely open. Our own research on the subject started in 1998. Our past contributions on the subject can be found in the previous activity reports and in [21][22]. They have been successfully validated on our experimental mobile robot ANIS. New developments are currently carried out in the context of the *Programme d'Etude Amont: MiniROC* funded by the *DGA (Délégation Générale à l'Armement)*. Within this program, ICARE is in charge of the localization and mapping workpackages.

This year, our research has focused on two issues : i) the design of a robust Bayesian estimator for the acquisition and updating of the laser signals used in the sensor-based control navigation, ii) the correction of the distortions on the global map induced by the SLAM process, by using a minimization approach based on a semi-elastic model.

6.2.1.1. Bayesian segmentation of range laser scans :

By using the Bayesian estimation theory, we have developed a new probabilistic version of the Hough transform in order to extract and track line segments in successive laser range scans [42]. In our method, a likelihood function associated with the objects surrounding the robot is defined, and a probabilistic model for the telemetric data is derived and used in order to update this likelihood function. In this way the distances between the robot and the surrounding objects are estimated, and can then be used in the feedback loop of a sensor-based control navigation strategy. Experiments performed with a mobile robot equipped with a 2D laser scanner device have validated the application of the Bayesian segmentation methodology in the laser-based robot navigation.

6.2.1.2. Global optimization of the laser map based on a semi-elastic model :

We have proposed in [41] a robust modeling approach for the exploration of large scale indoor environments. The model of the environment is structured as an hybrid geometrical/topological representation, and is built incrementally during the exploration task. The geometrical component of the model is a precise description of the borders of the robot's free space, while the topological component represents the connectivity and accessibility of the different regions in the environment. We have shown that the duality inherent to this hybrid representation contributes to the robustness of the navigation process. The environment is partly composed of a collection of distinctive *places*, each one associated with a local reference frame with respect to which the robot can be localized with a good precision. The relations of connectivity between the different places are essentially topological in nature and are captured by a graph representation. The robot can be localized in a multi-scale manner from this hybrid model, either *precisely* when exploring a specific place, or *coarsely* when traveling between two different places. In this way, the precision of the geometrical model is combined with the robustness of the navigation strategy provided by a topological representation. However, the lack of a precise metrics between the different places introduces *inconsistencies* on the global model when the robot comes back to a place previously explored. This is a known problem of closing loops in the autonomous mapping process.

To address this issue, we have proposed an optimization technique based on a semi-rigid modeling of the environment : the topological connections between places are modeled as *elastic constraints*, whereas the geometry of the environment at a given place is described by *rigid constraints*. We minimize a global energy function measuring the discrepancies between local observations and the shape-adaptable model which explicitly takes into account the quality of the estimation of the robot's motion and the rigidity constraints of the local environment. Figure 1 shows the results of the elastic correction of the global model by applying this methodology.

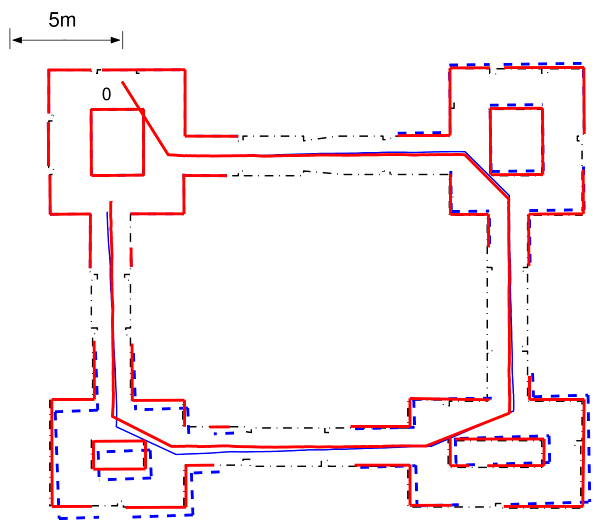


Figure 1. The propagation of the elastic correction of the localization error in the global metric model

6.2.2. Omnidirectional vision for navigation

The strength of laser-based SLAM systems comes from the bearing information which they provide, and also their large scan range (180° or 360° generally). However, compared to vision-based systems, they have a low degree of discriminancy. Correct laser registration, in corridor environments for example, is impossible and the localization information needed for closed-loop control is also hard to obtain. These issues have led us to look for solutions with vision-based systems which naturally provide a rich information.

Panoramic vision and, in particular, Central Catadioptric vision constitute emerging research topics in Robotics. In the case of Simultaneous Localization And Mapping (SLAM), these sensors yield better precision and improved robustness. For SLAM purposes, obtaining large fields of view can be achieved mechanically by using a rotating camera. However such devices hardly comply with the real-time implementation constraints imposed by sensor based control. Fisheye lenses have a field of view broader than classical cameras, but it is always much narrower (∼90°) than the laser range finder scan area. As a consequence, it is still necessary to combine data collected from different views. Catadioptric sensors, consisting of cameras pointing upwards towards a convex mirror, make it possible to obtain a 360° field of view with no rotating mechanical part being involved. Their drawback is the nonlinearity of the projected view and the way the camera pixels are spread out. These characteristics depend on the mirror's shape. Mirrors with a single focal point allow to generate correct perspective images that are useful for 3D reconstruction, and also make the projection model simpler in theory. Only three types of mirrors have this property : elliptic, parabolic and hyperbolic. The parabolic mirror, whose calibration is easier and which generates simpler projection models, has been chosen for our project.

For the simulation of our algorithms, a program based on the Povray ray tracer was written. Used in conjunction with KPovmodeler, complex and realistic environments for simulation can be generated (Fig. 2).

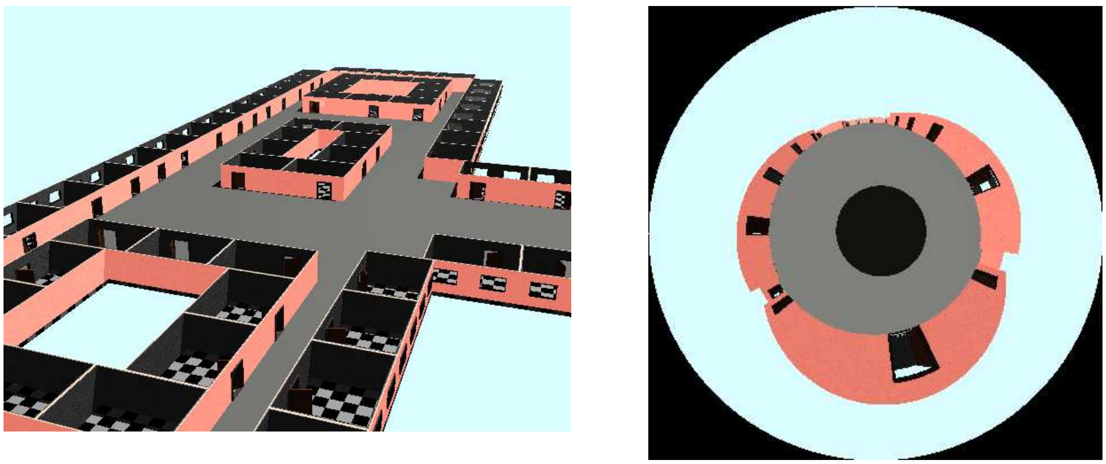


Figure 2. Simulated images

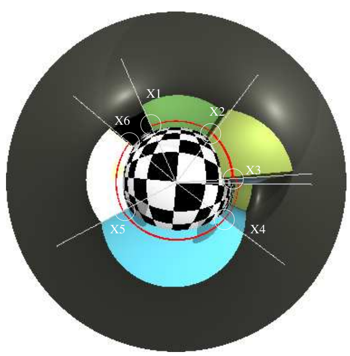


Figure 3. Points correspondence for the calibration between a data laser range finder and an omnidirectional vision sensor

The theoretical contribution of our work concerns the calibration between a laser range finder and an omnidirectional sensor. We have shown that calibration is possible from a single image with a laser range finder which emits in the visible red spectrum. Four correspondences between laser points and images are necessary. Figure 3 shows the extraction of corresponding points based on the intersection between vertical landmarks (obtained using a Hough transform) and the laser signal.

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

The robust localization of a vehicle in an urban environment remains one of the main challenges in order to achieve autonomous navigation in city streets. By using a stereo-vision sensor, we propose to construct a 2.5D model of the vehicle's environment. An important difficulty is to discriminate the road plane from other coplanar features (edges, feature-points) present in the image. The matching of these features between two consecutive images then allows to compute an homography which provides an estimation of the vehicle motion between these images. The stereo-vision system, composed of two weakly calibrated cameras, makes it possible to cope with dynamical obstacles on the road (pedestrians, vehicles), using the fact that the features induced by them do not verify the homography of the road plane between the cameras of the stereo rig. This year, our work has consisted in improving the robustness of our method w.r.t. various urban traffic conditions. We are now able to track the painted lanes on the road plane based on the detection of only one of them [39][40]. We hence know the borders of the road plane. In the same way, we use the super-homography computation to introduce the epipolar and temporal constraints between the features coordinates detected in several views. Such a method has three main benefits. Firstly, the super-homography computation improves the robustness of the algorithm, because only the coplanar features verify the constraints over several views. Then, the coordinates of the coplanar features can be estimated with a sub-pixellic precision even when they are occluded in the current image (Figure 4). Finally, the use of these coordinates compensate for calibration errors, thus improving the reliability of the algorithm.

6.3. Robust visual tracking and control

Keywords: *camera calibration*, *camera invariants*, *nonlinear least-squares*, *parameters identification*, *robustness to parametric uncertainties*, *second-order minimization*, *stability analysis*, *structure from motion*, *target visibility*, *vision-based control*, *visual tracking*.

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

The practicality of sensor-based (and in particular of vision-based) control techniques for complex mechanical systems relies upon the capacity of producing precise movements, the simplicity of the setup procedure, the ease of portability on different systems and, above all, good robustness w.r.t. uncertainties. To achieve these objectives, several problems still need to be solved.

- To improve the precision, several different sensors must be used. For some applications, cameras are not sufficient. Other sensors (laser, force, ultrasonic...) can provide complementary and/or redundant information. The problem then is to design robot control laws capable of exploiting data issued from multiple disparate sensors.
- To simplify the setup, it is preferable to avoid any calibration procedure. Zooming cameras offer the possibility of improving the results by using the zoom during the task execution. In this case, the variation of the focal length must be taken into account in the design of the visual servoing method.
- 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, when the camera's calibration step is skipped, the control laws must be robust against uncertainties about the system's parameters. They should also have a large domain of convergence in order to allow for initial positions of the robot far away from the reference position.

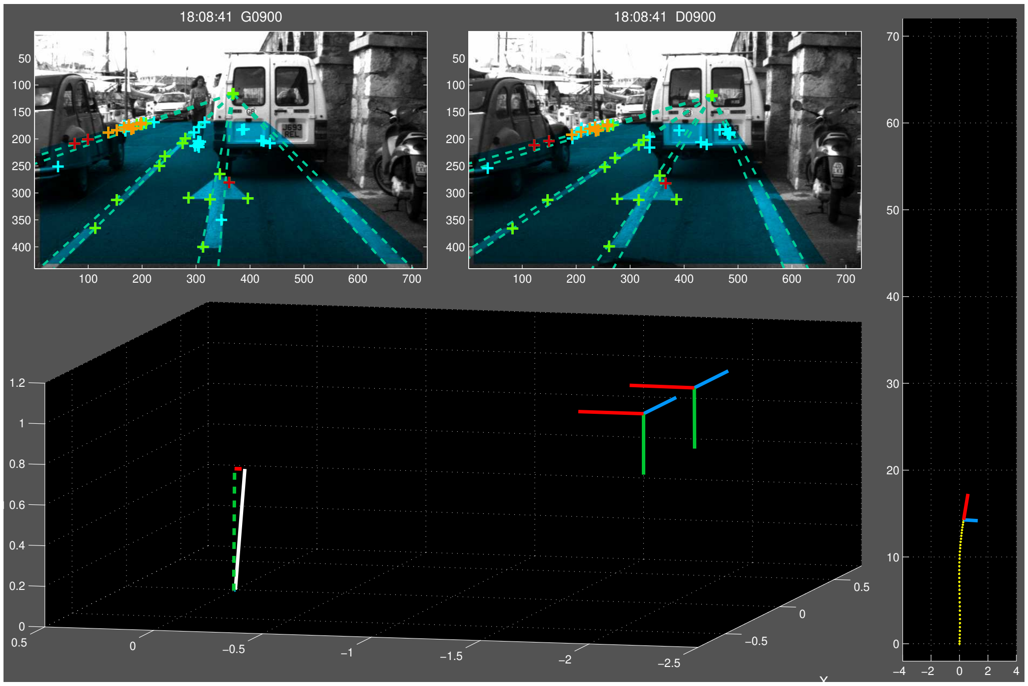


Figure 4. Top sub-figures: Extraction of features lying on the road plane (blue area). The borders of the road plane are detected via the tracking of the painted lanes which are assumed parallel and, therefore, converge to the Dominant Vanishing Point. The dashed green lines represent coplanar and parallel edge lines which are matched between the two images. The extracted feature points are cyan '+'. The green '+' ones are those which verify the Super-Homography constraints, they are lying on the road plane. The orange (red) '+' were not detected in one (two) current image(s). The computation of the Super-homography allows to estimate their current coordinates in the image(s). Bottom sub-figure: the right camera frame and the normal of the road plane are computed with respect to the left camera frame, assuming a generic internal parameters matrix for both cameras. Right sub-figure: a chronogram shows the path followed by the left camera from a bird-eye point of view.

6.3.1. Vision-based control

Vision-based robot control methods can be classified following an analogy with well known minimization methods (Cauchy, Gauss-Newton, Newton, ...). For instance, we show in [34] that standard vision-based control methods are generally based on first-order approximations, alike simple gradient optimization algorithms. Theoretically, the performance of vision-based control could be improved by using schemes endowed with the same properties as the Newton minimization algorithm, which involves second-order approximations. Unfortunately, the calculation of second-order derivatives can be ill-conditioned, thus yielding convergence problems. In order to solve this type of problem we have proposed in [34] new control schemes based on second-order minimization techniques. By using first-order derivatives to calculate second-order terms approximately, these schemes are computationally efficient and appear to perform well in practice.

6.3.2. Real-time visual tracking

A real-time visual tracker is a fundamental part of a visual servoing system. Several feature-based tracking algorithms have been incorporated in our visual servoing schemes: tracking of closed contours, straight lines, and interest points. Unfortunately, feature-based tracking methods are sensitive to feature detection failures. In addition, the choice of an adequate feature-based tracking algorithm depends on the type of features which are available in the scene. For example, an algorithm designed for tracking straight lines in the image cannot be used for tracking objects that have only interest points. By contrast, template-based visual tracking algorithms do not depend on features. For this reason they are better suited for visual servoing [33]. We have proposed a template-based tracker for planar objects the shape and texture of which can be (almost) arbitrary [28]. Instead of extracting visual features like interest points, lines, or contours, the homography which encodes the 3D motion of the plane is estimated directly from pixel intensities. Compared to standard template-based visual tracking systems, the approach proposed in [28] is based on a second-oder minimization technique [34] which improves its efficiency.

The new algorithm has been tested on several video sequences involving moving planar objects. Two sets of four images taken from two different sequences are shown in the first rows of Figures 5 and 6. In the case of the first sequence, the template attached to the object that we wish to track is the red window displayed in the first column of Figure 5. The subsequent windows are warped back in the reference frame by using the homography estimated with our tracking algorithm. The results of this process are shown in the second row of Figure 5. Despite illumination variations and image noise, the warped windows look much alike the reference template, thus proving that the tracking is accurately performed. For the second video sequence, a camera inside a moving car observes another car parked on the side of the road. The selected reference template is centered on the rear doors of the parked car. Again, the tracking is accurately performed, despite the fact that the observed region has slightly changed in the mean time (due to the passage of pedestrians in front of the parked car, seen through the car windows) and does no longer correspond to the initial reference template.

6.3.3. Stability analysis

In order to improve the robustness of sensor-based control laws, it is important to carry out a stability analysis. Indeed, calibration errors on some parameters used in the control laws can reduce the performance of the system (the system can even become unstable). For example, in [7], we have studied the stability domain of the visual servoing method proposed in [3] by considering interest points as image features. In this case, the method relies on an estimation of the depths of the 3D points. We have found that the robustness with respect to estimation errors is very limited. The stability analysis proposed in [7] has been extended to general central catadioptric cameras in [35], yielding similar results.

6.3.4. Visibility of image features

This work deals with the problem occurring when features go in or out of the image during a visual servoing task. The appearance/disappearance of image features during the control task produces discontinuities in the control law which affect the performance of the system. When one or more features appear or disappear during the servoing process, they are either added to, or removed from, the error vector (Figure 7). This produces a discontinuity in the control law the magnitude of which depends on i) the number of involved features, ii)

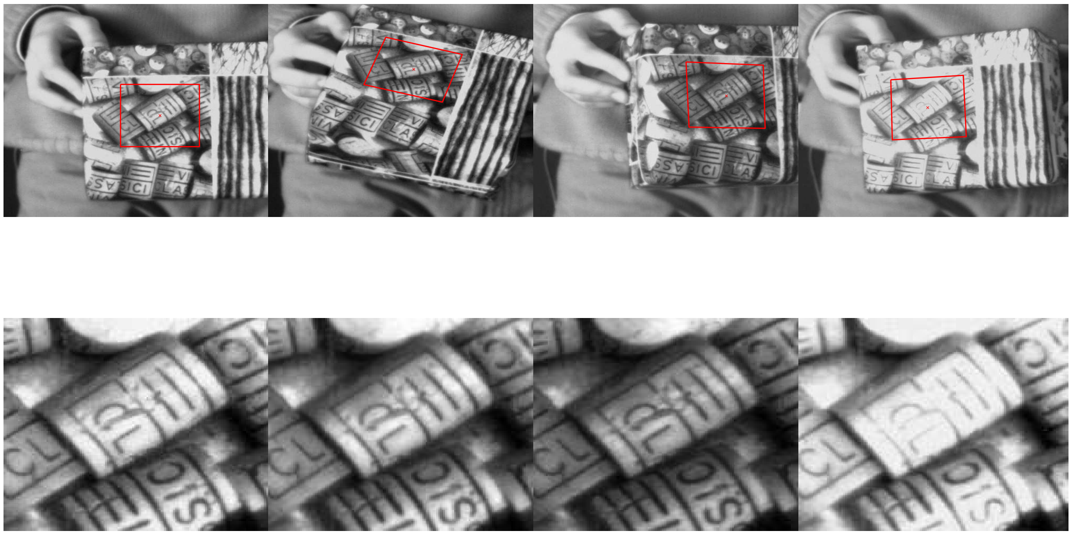
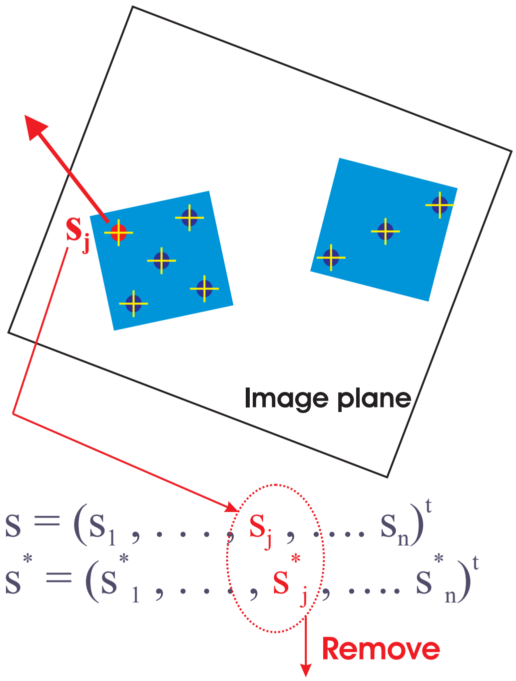


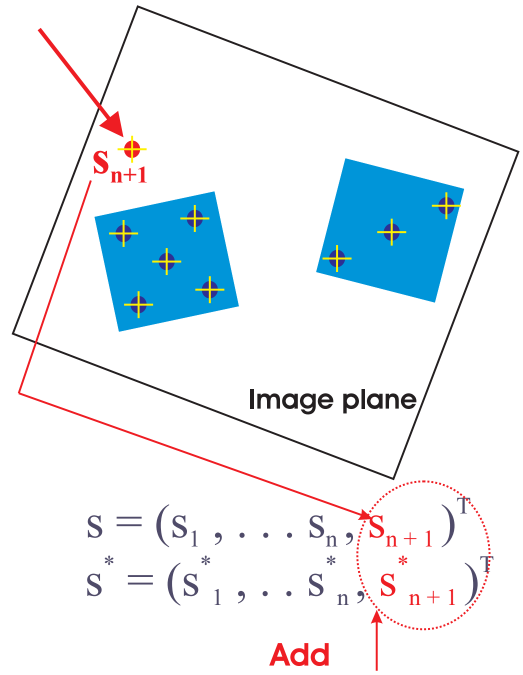
Figure 5. Tracking a planar object.

Figure 6. Tracking the rear of a parked car.

the distances between the current and reference features, and iii) the conditioning of the pseudo-inverse of the interaction matrix. In [35], we have proposed a solution to avoid these discontinuities by using weighted image features. In particular, we have adapted the camera-invariant visual servoing approach of [24] so as to take into account the modifications occurring in the image features during the positioning task, when zooming in or out. Simulations and experimental results illustrate the improved performance of the vision-based control task.



(a) Disappearance of an image feature



(b) Appearance of a new image feature

Figure 7. Appearance and disappearance of features in the image plane.

6.3.5. Correction of the lens distortion for zooming cameras

The output of a visual tracking system is generally given in the projective space. In order to recover the displacement of the camera in the Euclidean space, one needs to know the camera intrinsic parameters. They can be obtained via an off-line calibration procedure. However, in some robotic applications, using self-calibration is preferable. This becomes necessary if we use a zooming camera. For this reason, we have proposed self-calibration algorithms which estimate the intrinsic parameters of such a camera [6], and also the lens distortion [29] [27]. The method proposed in [29] does not require any special calibration pattern, nor does it rely on the presence of special structuring features (e.g. straight lines) in the environment. This is consistent with our goal to self-calibrate a zooming camera mounted on a robot exploring unknown and unstructured environments. With our method, no robot motion is required for the self-calibration of the lens distortion, and only two images acquired with different zooming values are needed. By matching a distorted image with an undistorted one at different resolutions, it is also possible to correct the distorted image. The matching and self-calibration algorithm make use of invariants w.r.t. pinhole camera parameters. As an example, Figure 8 illustrates the possibility of estimating and correcting the lens distortion of the camera by using natural images.

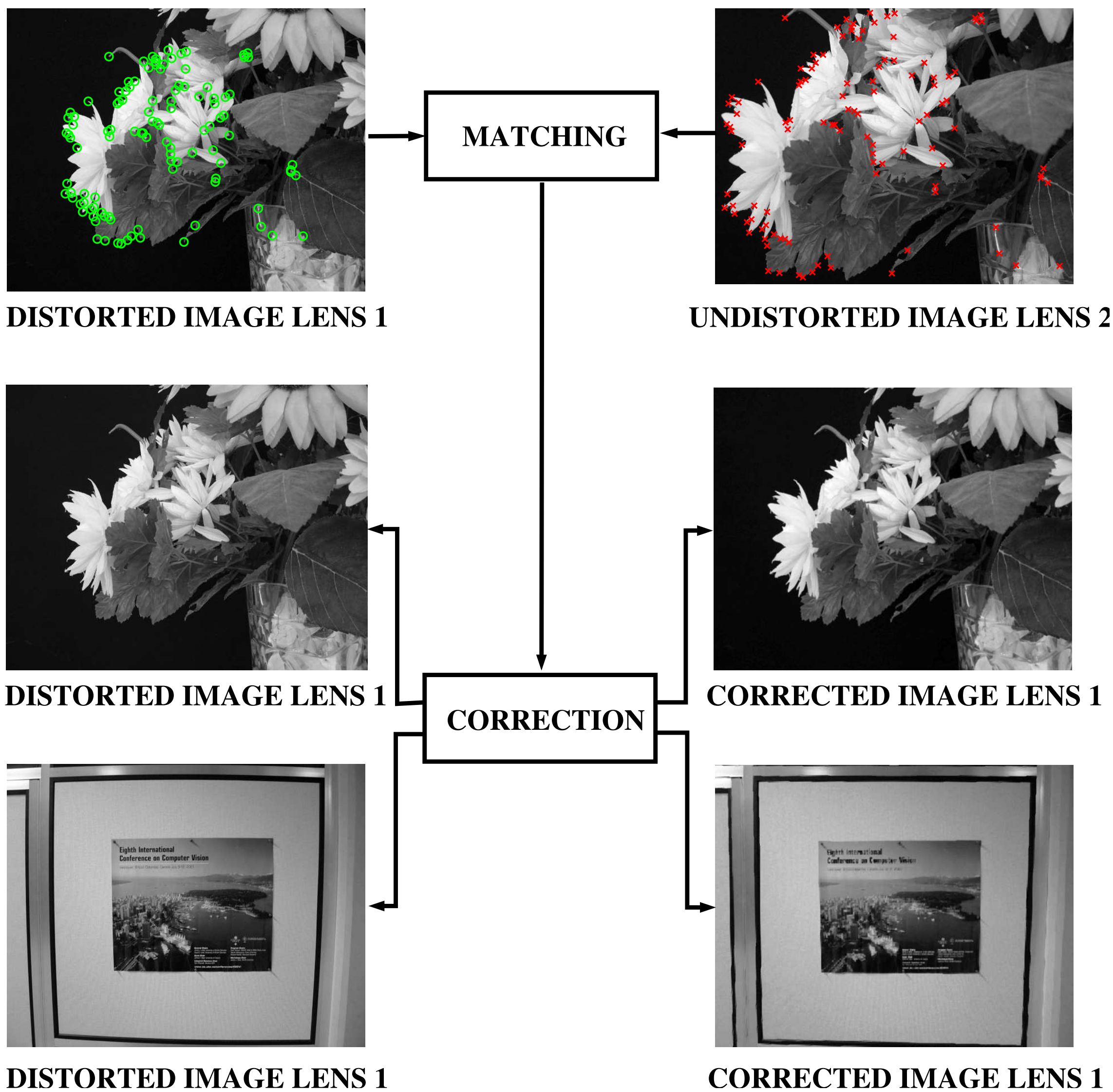
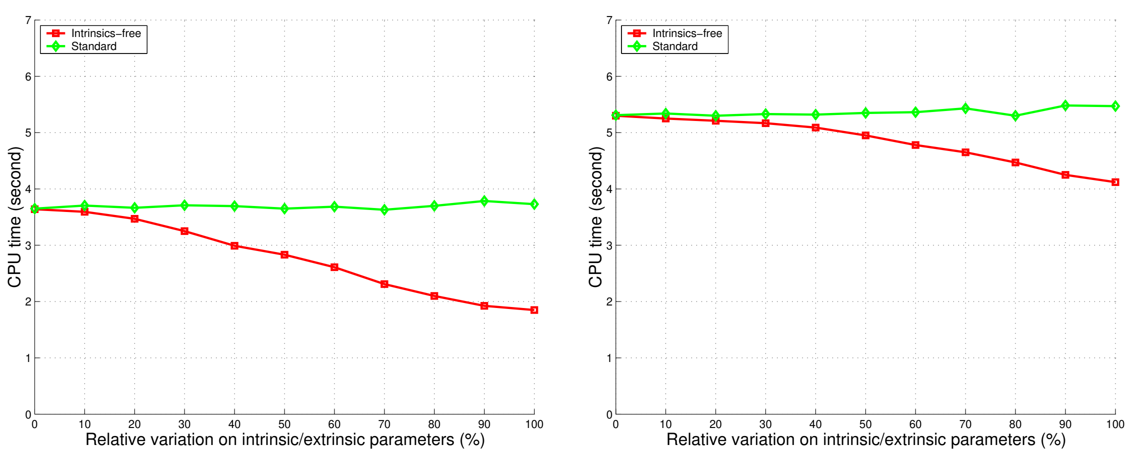


Figure 8. The image matching used to correct the short focal length distortion.

6.3.6. Euclidean reconstruction independent of camera intrinsic parameters

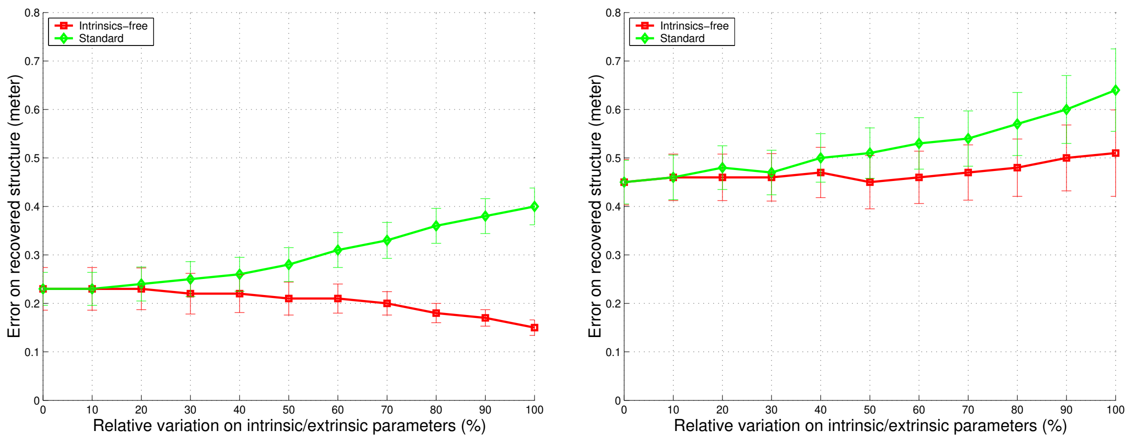
Euclidean reconstruction involves a costly optimization over many images (called bundle adjustment). Standard bundle adjustment techniques use measurements which depend on the (unknown) camera intrinsic parameters. For this reason the estimation of these parameters is included in the optimization process. In [32], we have shown that the knowledge of the camera intrinsic parameters is not needed for Euclidean reconstruction, provided that the measurements used for the reconstruction do not depend on these parameters (use of invariants). The computational cost of the optimization is then reduced and, since less unknown parameters are estimated, the convergence is faster. Moreover, the camera intrinsic parameters do not have to be constant, thus allowing for the use of zooming cameras. The bundle adjustment proposed in [32] posseses these useful properties while providing results with the same accuracy as standard methods. In order to illustrate the gain in performance resulting from using our algorithm, we have performed a simulation involving seven zooming cameras with the objective of tracking a deformable object and estimating its motion w.r.t. the cameras. At each iteration the object's structure and motion are estimated via a bundle adjustment procedure. The estimation result at iteration k is the starting point of iteration $k+1$. The object is maintained approximately at the center of the images by zooming and changing the cameras' orientations. Therefore, the cameras intrinsic and extrinsic parameters vary continuously. The deformation of the object through time is produced by offsetting the position of each object's point with a random value drawn from a normal distribution of variance roughly equal to 10% of the object's size. Figure 9 shows the needed CPU time depending on whether the object is rigid (a) or deformed (b). The object motion is a weighted combination of a circular motion, which induces important modifications in the cameras' orientations and small ones in the intrinsic parameters, and a translation away from the cameras inducing effects of inverse importance. Figure 9(a) shows that, when the variations in the cameras' orientations are dominant, the performances of the standard and intrinsic-free bundle adjustments are not very different (with a small advantage to the intrinsics-free method). On the other hand, when the object moves away from the cameras, the large variations in the parameters tend to augment the differences between the two algorithms. The intrinsics-free method also consumes less CPU time. Figure 9(b) shows that, when the previous scenario is combined with a deformation of the object, the differences between the algorithms, although slightly smaller, remain significant when the variations in the intrinsic parameters are dominant.



(a) Rigid structure (b) Non rigid structure

Figure 9. CPU *time to convergence versus relative variation k on camera parameters. When $k = 0$ % only the camera extrinsic parameters vary. When $k = 100$ % only the camera intrinsic parameters vary.*

The reduction in the number of estimated parameters has also a beneficial effect on the accuracy of the reconstruction, as shown on Figure 10. On the left sub-figure, we observe that when the structure is rigid and the camera intrinsic parameters vary, the intrinsic-free approach performs significantly better than the standard bundle adjustment. When the structure is non-rigid (right sub-figure), the differences between the two algorithms are smaller, but the intrinsics-free bundle adjustment continues to be more accurate.



(a) Rigid structure (b) Non rigid structure

Figure 10. Error on the recovered structure as a function of the relative variation k on camera parameters.

6.4. Visual servoing techniques applied to the control of aerial robots

Keywords: *aerial unmanned vehicle*, *aerodynamic Al modeling*, *sensor-based control*, *visual servoing*.

Participants: Patrick Rives, José-Raul Azinheira [Instituto Superior Tecnico (Lisbonne, Portugal)], Samuel Bueno [Information Technology Institute (Campinas, Brésil)], Geraldo Silveira [Information Technology Institute (Campinas, Brésil)].

The design of robust controllers for aerial unmanned vehicles requires solving many difficult problems mainly due to the large variability of the models during the different phases of flight (take off, cruise flight, landing). In practice, the autopilots currently used in the industry select the appropriate control law depending on the phase of flight. In the case of an airship with vectorized engines, the difficulties increase due to the existence of two radically different modes of flight (aerostatic versus aerodynamic flight) involving strong non linearities in the model. Another specificity is the difficulty of clearly defining which degrees of freedom are actuated. For example, in the aerodynamic mode, the control surfaces become efficient only when the air velocity is larger than a certain value. Conversely, in the aerostatic mode, due to the vectorization, the actuated directions of motion can change. In some cases the airship behaves like an underactuated system, while in other cases the means of actuation are redundant. Last year [12], we designed a LQR controller based on a time-varying linearized model, computed on line and parameterized by the air velocity and the altitude. We have applied a similar approach to derive visual servoing control schemes using an on-board camera in order to accomplish survey missions (road following, stabilization over a structure...) and execute critical flight phases, such as landing, autonomously. This work is done in collaboration with the Laboratory of Robotics and Vision at the CenPRA (Campinas, Brazil) and the Department of Mechanical Engineering at IST (Lisboa, Portugal) [20].

This year, our research on this subject has focused on the definition of well-conditioned visual servoing tasks for tracking linear structures in the environment like roads or rivers. It is assumed that the road (or river) can be modeled by two parallel curves which can be locally approximated by two parallel tangent lines L_1 and L_2. Executing the road following task requires to control five degrees of freedom (3 rotations and 2 translations) by using a visual servoing method. The remaining degree of freedom corresponds to the translation along the road axis and can be controlled separately. Assuming that the airship is flying in an aerodynamic mode, the problem is to define visual signals in the image which comply with the natural decoupling existing between the lateral and longitudinal dynamics of the airship. Moreover, we want the extraction of such visual signals from natural outdoor environments to be easy. In terms of decoupling, recent results obtained in geometrical vision point out interesting properties associated with the features in the scene that belong to the plane at infinity. It is simple to prove that the projection of such features onto the image depends only on the orientation of the camera and is independent of its position. We have used this property to decouple the control of the camera/airship's orientation in the visual servoing task. Using the horizon line and the vanishing point induced in the image by the two parallel tangent lines L_1 and L_2, we obtain the visual signals which can be used to control the three rotation degrees of freedom of the camera. Concerning the control of the camera's position, we use a combination of the parameters of the lines l_1 and l_2 (corresponding to the projections of L_1 and L_2 in the image) in order to get good decoupling properties for the lateral and vertical motions. Figure 11 illustrates a road following task with a front-to-lateral wind of 4m/s and airship longitudinal velocity of 8m/s. The dashed segments represent the different orientations of the airship during the flight.

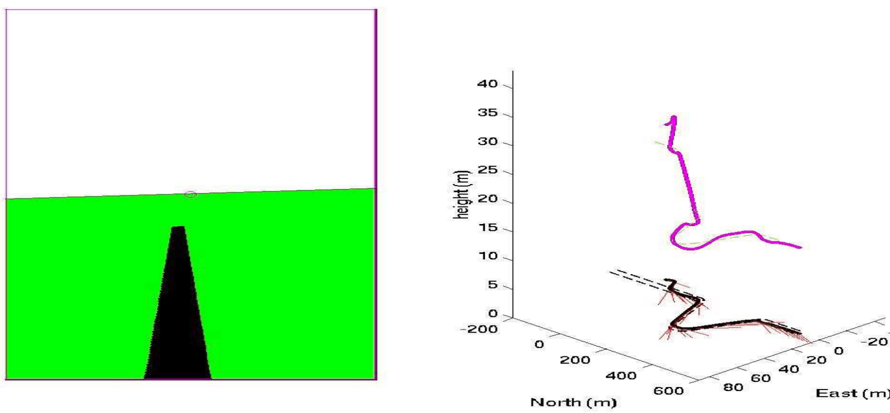


Figure 11. A road following task with strong lateral wind

7. Contracts and Grants with Industry

7.1. Project IST CyberCars

Keywords: *Urban vehicles*, *control*, *navigation*.

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

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

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

- « Automated maneuvering of nonholonomic wheeled vehicles » (G. Artus).
- « Localisation and navigation of an electrical car in an urban-type environment », (N. Simond).

7.2. Project MiniROC (ECA/DGA)

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

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

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

7.3. Project MobiVIP (Predit3)

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

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

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

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

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

7.4. Project Themis (Ifremer/Uratek)

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

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

This joint contract with the start-up company URATEK concerns extensions of F.X. Espiau's PhD Thesis on 3D vision-based modeling of natural underwater scenes. The objective is to design an active stereovision head controlled via visual servoing techniques. This work will be pursued in the context of a PhD thesis funded by the Ifremer Institute and the PACA region.

8. Other Grants and Activities

8.1. National Activities

8.1.1. CNRS research projects ROBEA

Participants: Claude Samson, Patrick Rives, Pascal Morin, Ezio Malis, Selim Benhimane, Matthieu Fruchard.

Icare participates in three research projects within the interdisciplinary CNRS/INRIA robotics program called ROBEA:

- **2001-2004** *COMMON Control of nonholonomic mobile manipulators*. Motion coordination between a manipulator arm and the nonholonomic vehicle on which the arm is mounted. How to combine nonholonomy and mechanical redundancy. ICARE is the project-leader team.
- **2001-2004** *AEROB Ground and aerial robots in outdoor environments*. On-line acquisition/modeling of the environment and safe vision-based navigation.
- **2003-2005** *BODEGA Safe Navigation in Urban Environments*. Dealing with the autonomous navigation of a car in an urban environment using vision and GPS sensors.

These projects are led in collaboration with university, CNRS research teams and other INRIA teams: LAAS (Toulouse), ENI (Tarbes), LSIIT (Strasbourg), CESBIO (Toulouse), LASMEA (Clermont Ferrand), UTC-HEUDIASYC (Compiègne), Germes (Limoges), Lagadic (Inria-Rennes), TexMex (Inria-Rennes).

8.2. European Activities

8.2.1. Joint research program INRIA/ICCTI

Within the joint research program between INRIA and ICCTI which started in 1998, Icare has an ongoing collaboration with the Department of Mechanical Engineering at the Instituto Superior Técnico (IST) (Lisboa). In 2003, P. Rives spent two weeks at the IST, and Prof. J.-R. Azinheira spent two weeks at INRIA Sophia Antipolis. From November 2003 to June 2004, Prof. Azinheira spent part of his sabbatical year with the ICARE team. This joint research focuses on the control of aerial unmanned vehicles by using visual servoing techniques. This bilateral action is part of a larger research program which also involves the Robotics and Vision Lab at CenPRA (Campinas, Brazil).

8.3. International Activities

8.3.1. Joint research program INRIA/CNPq

The project AURORA (*Autonomous Unmanned Remote Monitoring Robotic Airship*) led by the LRV/IA/CenPRA aims at the development of an airship dedicated to observation. Collaboration agreements on this theme were signed in 1999 between Inria, Brazilian CNPq, and Portugese ICCTI (see also the section *Joint research program INRIA/ICCTI*). In such a context, Geraldo Silveira has just begun this year a PhD thesis in the ICARE team with a funding from the national brezilian agency CAPES. On the other hand, the visual tracking algorithm developed in ICARE is currently transfered to the LRV/IA/CenPRA. Voir : 8.2)

9. Dissemination

9.1. Involvement in the scientific community

- C. Samson is a member of the Reading Committee for the SMAI (Société de Mathématiques Appliquées et Industrielles) book Collection on "Mathematics and Applications".
- E. Malis and P. Rives are co-organisators of the "5TH SUMMER SCHOOL ON IMAGE AND ROBOTICS" held in Sophia Antipolis in june 2004.

9.2. International conferences

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

- IEEE International Conference on Robotics and Automation, New Orleans, USA, April 26-30, 2004.
- IEEE Conference on Intelligent Autonomous Vehicles, Lisboa, Portugal, July 5-7, 2004 July 2003.
- IEEE/RSJ International Conference on Intelligent Robots Systems, Sendaï, Japan, Sept 28 - October 2, 2004.
- IEEE Workshop on Robot Motion and Control (RoMoCo'04), Puszczykowo, Poland, June 2004.
- International Symposium on Advances in Robot Kinematics, Sestri Levante, Italy, June 2004.

9.3. National conferences

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

- AFCET RFIA Reconnaissance des Formes et Intelligence Artificielle, Toulouse, France, January 2004.

9.4. Activities of general interest

- C. Samson is a member of the "Commission des Postes Associés de l'U.R. de Sophia Antipolis".
- P. Rives is a member of the "Comité de Suivi Doctoral de l'U.R. de Sophia Antipolis".
- P. Rives is a member of the *61^{e} Commission de Spécialistes de l'Université de Nice - Sophia Antipolis*.
- P. Rives is at the head of the R&D action VISA aimed to develop the applications in the field of the Intelligent Transport System (ITS).
- E. Malis is a member of the "Commission de Développements Logiciels de l'U.R. de Sophia Antipolis".
- E. Malis is a member of the *61^{e} Commission de Spécialistes de l'Université Blaise Pascal - Clermont-Ferrand*.

9.5. Education Through Research

- *Habilitation à diriger des recherches*

  – Pascal Morin, « Stabilisation de systèmes non linéaires critiques et application à la commande de véhicules », Université de Nice-Sophia Antipolis, Octobre 2004.

- *Current Research Students* :

  – G. Artus, « Automatisation de manœuvres de véhicules non-holonômes », École des Mines de Paris, supervisors : C. Samson, P. Morin.

  – S. Benhimane, « Asservissement visuel avec une optique à focale variable », supervisors : E. Malis, P. Rives.

  – M. Fruchard, « Commande de bras manipulateurs mobiles non-holonômes », École des Mines de Paris, supervisors : C. Samson, P. Morin.

  – M. Maya Mendez, « Commande référencée capteur des robots non-holonômes », École des Mines de Paris, supervisors : C. Samson, P. Morin.

  – N. Simond, « Localisation et navigation d'un véhicule électrique dans un milieu de type urbain », université de Nice-Sophia Antipolis, supervisor : P. Rives.

  – C. Mei, « Cartographie et navigation autonome dans un environnement dynamique », École des Mines de Paris, supervisor : P. Rives.

  – G. Silveira, « Application de l'asservissement visuel au contrôle d'un drone aérien », École des Mines de Paris, supervisors : P. Rives, E. Malis.

  – V. Brandou,« Stéréo locale et reconstruction 3D/4D », université de Nice-Sophia Antipolis, supervisors : E. Malis, P. Rives.

- *Participation in Ph.D. and H.D.R committees* :

  – C. Samson has partipated in two HDR defense jurys.

  – P. Rives has participated in four Phd defense jurys.

- *Training periods* :

  – T. Alfaro, « Trajectory stabilization of general N-trailers by the transverse function approach », 5 months, supervisor : P. Morin

  – L. Pizarro, « Robust visual tracking », 5 months, supervisor : E. Malis

  – F. Bridon, « Spécification de l'architecture distribuée d'ANIS sous Linux/RTAI », 6 months, supervisor : P. Rives.

  – M. Vargas, « Robust visual servoing », 6 months, supervisor : E. Malis.

9.6. Teaching

- Lecture courses at the “École Nationale des Télécommunications de Bretagne”: *Machine Vision* (P. Rives, 3 hours).
- Lecture courses at the “5th Summer School on Image and Robotics” (INRIA Sophia Antipolis, France) *Sensor-based Control* (P. Rives, 6 hours).
- Lecture courses at the “École des Mines de Paris”, section “Automatique et Robotique”: *Visual Servoing* (E. Malis, 3 hours).
- Lecture courses at the “5th Summer School on Image and Robotics” (INRIA Sophia Antipolis, France) *Visual servoing and Visual Tracking* (E. Malis, 6 hours).
- Lecture courses at the “5th Summer School on Image and Robotics” (INRIA Sophia Antipolis, France) *Feedback control of nonholonomic mobile robots* (P. Morin, 3 hours).

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