

*Project-Team icare**Instrumentation, Commande et
Architecture des Robots Évolués**Sophia Antipolis*

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Table of contents

1. Team	1
2. Overall Objectives	1
3. Scientific Foundations	1
3.1. Robots and control	1
3.2. Control of nonlinear systems	3
3.3. Perception for modeling	4
3.3.1. Geometrical modeling	4
3.3.2. Recognition of known structures	4
3.4. Mobile robot navigation	5
3.4.1. Perception and task planning	5
3.4.2. Perception and execution control	6
3.5. Means of experimentation	6
4. Application Domains	7
4.1. Panorama	7
4.2. Automatic driving	7
4.3. Observation aerial drones	8
6. New Results	8
6.1. Stabilization of mobile robots and of nonlinear systems	8
6.1.1. Practical and asymptotic stabilization of driftless nonlinear systems by the transverse function (t.f.) control approach	9
6.1.2. Control of nonholonomic mobile manipulators	9
6.1.3. Control of maneuvering car-like vehicles	11
6.1.4. Vision-based control of a unicycle-type vehicle: experimentation and complementary control aspects	11
6.1.5. Field-oriented control of induction motors	11
6.2. Mobile robot navigation and guidance	11
6.2.1. Simultaneous Localization and Mapping (SLAM) in unknown indoor environments	12
6.2.2. Accurate localization of a car-like vehicle in an urban environment	14
6.3. Uncalibrated visual servoing in unknown environments	15
6.3.1. Vision-based control using a zooming camera	15
6.3.2. Robustness of image-based visual servoing	16
6.3.3. Uncalibrated active affine reconstruction	16
6.3.4. Matching points with different image resolutions	17
6.4. Visual servoing techniques applied to the control of aerial robots	18
7. Contracts and Grants with Industry	19
7.1. Project IST CyberCars	19
8. Other Grants and Activities	20
8.1. National Activities	20
8.1.1. RTP « Systèmes Aérospatiaux » (CNRS)	20
8.1.2. CNRS research projects ROBEGA	20
8.2. European Activities	20
8.2.1. Joint research program INRIA/ICCTI	20
8.3. International Activities	20
8.3.1. Joint research program INRIA/CNPq	20
9. Dissemination	20
9.1. Involvement in the scientific community	20
9.2. International conferences	21

9.3. Award	21
9.4. Activities of general interest	21
9.5. Education Through Research	21
9.6. Teaching	22
10. Bibliography	22

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2. Overall Objectives

The project activities concern the modeling and control of mechanical systems (manipulator arms, mobile robots, underwater vehicles,...) equipped with sensory devices (ultrasonic sensors, laser range finder, camera, inertial navigation system,...) and destined to accomplish complex tasks strongly interacting with the system's environment.

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. 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, that the project will use in future experimentation, 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 instance 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. Robots and control

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

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

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 correspondance 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.

3.2. Control of nonlinear systems

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

Key words: *nonlinear system, feedback control stabilization, robust 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 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 [39]. 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* [38], used to solve trajectory planning problems, and *time-varying feedback control* techniques [32], 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 [11] which is a general framework for addressing sensor-based control problems. As for our studies about mobile robot control [12], 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* [36] for “highly” nonlinear systems.

3.3. Perception for modeling

Participants: Patrick Rives, Ezio Malis, Jean-Jacques Borrelly, Alessandro Corrêa-Victorino, François-Xavier Espiau.

Key words: *active perception, image processing, laser proximity, 3D reconstruction, cartography.*

The realization of a robotic task requires acquiring and manipulating models of the environment obtained by processing information provided by exteroceptive sensors. Sometimes, the finality of the task is the construction of these models itself. Other times, these models will serve as inputs to a planning module or be used directly in the control loops. In all cases, the reliability of the representations, and thus of the means of perception which allowed to construct them, is essential to the effective realization of the task. Exactly like humans, robots exert actions that are governed by the laws of physics. This characteristic underlies the manipulated models which, most of the time, are surfacic or volumic tridimensional representations, described with respect to some euclidean frame and submitted to the action of the (Lie) group of displacements whose Lie algebra is the set of velocity screws. Unfortunately, the exteroceptive sensors used in robotics are seldom capable of providing models of this type directly, so that an important part of the modeling work will consist in passing from the raw data provided by the sensors to the model needed to execute the task. The spectrum of problems in robot perception is very large, with two types of problems which can be called canonical :

- **geometrical modeling** : given a set of sensory measurements, this consists in constructing a geometrical representation of the environment,
- **recognition of known structures** : this consists in detecting from sensory data a specific structure, or feature, present in the environment and often described by a generic model characterizing a class of objects.

3.3.1. Geometrical modeling

Historically, the problem of geometrical modeling is related to the manipulation of objects by industrial manipulators. It then consisted in the reconstruction of geometrical objects with a relatively simple shape, a model of which was known, and located inside a limited workspace volume. The methods used to this purpose were mostly driven by the models in order to best exploit the *a priori* knowledge about the application. Mobile robotics has introduced new types of problems due to that :

- the operating space of the robot is large and its localization within this space is often uncertain,
- the models which have to be constructed may bear upon unstructured natural objects whose complete observation requires moving the sensors and merging several partial perception data sequences,
- the robot's positions and displacements during data acquisition are not known precisely.

In this context, the model driven approaches prove to be ineffective most of the time. Hence, it is important to devise robust reconstruction methods which rely as much as possible on measured data and only keep elementary properties, such as the rigidity of an object, from the model approach. The success of these methods then largely depends on the quality of the algorithms used for data measurement acquisition and processing.

Within the project ICARE, we have so far mostly dealt with two kinds of sensory modalities often used in mobile robotics : telemetry and vision. The methods that we develop are based on the robust detection of local geometrical primitives that are stable and characteristic of the environment. The coherence between these local primitives is ensured by the rigid body constraint expressed in the form of a graph. The model so obtained is updated during the robot's displacements via robust filtering techniques.

3.3.2. Recognition of known structures

Shape recognition and scene analysis are difficult research themes which have, for many years, motivated numerous studies in the domain of perception. In the context of intervention mobile robotics, the recognition modality is one of the basic modalities needed by the robot to execute its tasks. For instance, after an accident

or a natural disaster, the robot has to be able to identify passages (doors, corridors, staircases,...) allowing it to continue its exploration and update a topological description of the surrounding environment. It may also have to recognize certain objects in its environment (for demining operations, for example). As for the scientific content, this theme is extremely rich due to the necessity of defining incomplete and uncertain models and managing both the prior knowledge and the one acquired via sensory measurements along the robot's displacements. The modeling aspect has to take into account the geometrical variability of the model classes (doors, corridors,...) and also provide representations that are invariant with respect to observation (treatment of occlusions and of various geometrical "aspects"). In this context, model learning issues naturally arise. Decision taking aspects require to manipulate uncertainties about the sensors and models, and must rely upon a recognition strategy.

We have developed an approach based on the use of bayesian networks and an active perception strategy [2] for the search and identification of characteristic structures in the environment (doors, windows) which may serve as landmarks or represent passages between the different regions of a topological model.

3.4. Mobile robot navigation

Participants: Patrick Rives, Ezio Malis, Jean-Jacques Borrelly, Alessandro Corrêa-Victorino.

Key words: *sensor-based planning and control, visibility map, reactivity and safe navigation of a mobile robot, localisation, vision and telemetry sensors, multisensory cooperation.*

The navigation and control problems associated with so-called *autonomous* or *semi-autonomous* devices have long been confined to the domain of intervention robotics. Nowadays, they are open to numerous other application fields : transportation, individual vehicles, aerial drones, observation underwater devices,... In all cases, the issue is to make systems operate safely in imperfectly known environments by controlling the interaction between the vehicle and its environment. This interaction may take different aspects : actions from the robot (positioning with respect to an object, parking car maneuvers,...), reactions to events coming from the environment (obstacle avoidance, 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. Firstly, along the process of planning the task, this involves the acquisition, modeling, and manipulation of knowledge about the environment and the task. Then, during the task execution, the issue is to exploit the perception data so as to best adapt the system's behavior to the task specificities.

3.4.1. Perception and task planning

The modeling of the environment in view of planning the actions of a robot is a major theme in Robotics[7], [8], [33]. There are numerous ways of addressing this issue, depending on the *a priori* knowledge that one has about the environment. The spectrum of possible situations is large, ranging from the case when this knowledge 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 the model during an initial exploration phase is required. It is customary to distinguish different problematics depending on the purposes for which perception is used. For instance, this can be for i) motion planning, or ii) localization purposes. In the first case, one has to further distinguish between the construction of *geometrical models* used for the calculation of *cartesian trajectories* that are admissible in the free configuration space of the robot and the construction of *topological models* destined for the planning of navigation corridors and allowing to represent the accessibility between the different region *locations* of the environment. As for the geometrical models, in the case of indoor environments, they will often be reduced to polygonal representations of the obstacles calculated from the information produced by proximity sensors (ultrasonic, laser range finder,...). 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. 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). 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.

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, when the environment is not known *a priori*. The approaches which we are developing are based on two ideas : i) combine proprioceptive and exteroceptive sensory data for a better cooperation, ii) use sensor-based control laws to enforce constraints on the problems of localization and geometrical modeling and, subsequently, improve their conditioning. [40].

3.4.2. Perception and execution control

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 [37]. 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. In the case of perception, these two aspects can be elegantly addressed by using the formalism of *logical sensors* introduced by Henderson [34].

One of the project's research directions is devoted to the design and analysis of sensor-based control laws. The formalisms that we use for this purpose (task-functions, virtual linkages) allow to define these control laws at all levels of specification up to their implementation on a physical system. 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

Participant: Jean-Jacques Borrelly.

The project Icare develops and maintains an experimental platform dedicated to indoor mobile robotics.

- *Mobile platform with perception instrumentation*
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 digital movie camera attached to the manipulator's end-effector, and a laser range finder located on top of the first manipulator's articulation.
- *Vision system*
It is made up of a low-level task processing electronic card (windows management, time-convolutions, extraction of points of interest,...), an intermediary-level task processing card based on four DPS96002 modules (determination of characteristic parameters associated with features of interest inside a window), and a general usage processing card for the management of all high-level processing tasks.

- *Laser range finder*
The laser range finder ACCURANCE-4000 has a range of about fifteen meters, uses a rotating mirror to perform sweeping scans, and acquires a horizontal section made of 2000 measurement points in 40 milliseconds.

Since May 2001, the *Visa* team, directed by P. Rives, is in charge of an experimental platform at INRIA Sophia-Antipolis based on an instrumented electrical car 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,... The project is involved at this application level via national and international collaborations. Nowadays, these collaborations concern more specifically the theme of future transportation systems, with a participation in the European Project CYBERCARS, 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

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

Participants: Claude Samson, Patrick Rives, Ezio Malis, Pascal Morin, Jean-Jacques Borrelly, Guillaume Artus, Nicolas Simond.

The development and management of transportation means, in urban and inter-urban zones, have 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. Observation aerial drones

Key words: *modeling and control of aerial devices, drone, blimp, visual servoing.*

Participants: Patrick Rives, Samuel Bueno [CenPRA de Campinas (Brésil)], José Raul Azinheira [IST de Lisbonne (Portugal)].

Our collaboration with the CenPRA of Campinas and IST of Lisboa participates in the general theme of design and control of aerial vehicles (*drones*) destined to realize missions of surveillance and intervention either completely autonomously 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 Portuguese ICCTI. This cooperation is continuing and promotes missions of exchange among the participating researchers. At Inria, we are more particularly in charge of studying the contribution of visual servoing techniques for the automatization 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.

6. New Results

6.1. Stabilization of mobile robots and of nonlinear systems

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

Key words: *nonlinear system, asymptotic stabilization, practical stabilization, time-varying control, Lie group, mobile robot, manipulator arm.*

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 constraints 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 [5][16][15], 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. *Practical and asymptotic stabilization of driftless nonlinear systems by the transverse function (t.f.) control approach*

The t.f. approach provides a design method for the practical stabilization of nonlinear driftless system, i.e. the stabilization of a pre-defined set contained in a “small neighborhood” of a given state. While such stabilizers can also be derived from time-varying (periodic) asymptotic stabilizers, those obtained by the t.f. approach present two complementary features (see [15] for details) i) the ability to ensure practical stabilization even when an *arbitrary* perturbation is added to the system dynamics, ii) the possibility of stabilizing arbitrary trajectories in the state space, when the control vector fields are invariant with respect to a Lie group operation (e.g. unicycle kinematic equations, chained systems, homogeneous approximations, etc).

The problem that we have addressed was to ensure, in addition to practical stability, the asymptotic stabilization of a given point when the above-mentioned perturbation term is zero, or the convergence of the system’s trajectories to this point when the perturbation term tends to zero. A typical application of this is the trajectory stabilization problem (e.g. car tracking with an automatic vehicle) when one does not know in advance whether the reference trajectory of interest converges to some fixed point. In this case, we want to guarantee practical stability of the reference trajectory unconditionally, and also asymptotic convergence to the trajectory’s end-point whenever this point exists.

We have provided i) a solution to this problem for the class of chained systems, and ii) a general approach which might be used to obtain solutions for other systems on Lie groups. The approach is based on what we have called *generalized transverse functions*. By comparison with classical *transverse functions* $f(\theta)$, these new functions depend on an extra set of variables β , i.e. $f(\theta, \beta)$. While θ is again used to guarantee practical stability, the new variable β provides a new set of control parameters which allows to monitor the system’s behavior on the zero-dynamics. By analogy with the center-manifold theory, θ is used to ensure exponential convergence of the system’s state to the center manifold, while β is calculated so as to yield asymptotic stability on the center-manifold. In this way, by a proper definition of the generalized transverse function f , and of the dynamics β , it is possible to meet both objectives of practical and asymptotic stability. This work has given rise to a research report [30] and has been accepted for publication in an international journal [14].

6.1.2. *Control of nonholonomic mobile manipulators*

Our research on this topic corresponds to our participation in a project involving three other robotics laboratories (LAAS-CNRS of Toulouse, LGP-ENI of Tarbes, and AVR-LSIIT of Strasbourg), within the national program ROBEA (see Section 8.1) 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).

During the first year of the project, i.e. last year, we treated the supposedly simpler case of a redundant and holonomic mobile manipulator (with an omnidirectional mobile base) by revisiting and adapting the formalism of *task functions* [11]. The proposed methodology has been more specifically applied to the problem of tracking a moving object observed by a camera mounted at the tip of the manipulator’s end-effector (vision-based control), and the obtained control laws have been tested and validated in simulation.

We have this year started to address the case of a mobile manipulator whose base is subjected to nonholonomic constraints. As recalled earlier, the difficulty in controlling nonholonomic systems is essentially related to the fact that linear approximations of these systems, at an equilibrium point, are not stabilizable. The t.f. approach which we have been developing for a few years is an alternative to other feedback control approaches devised to stabilize these systems. As evoked before, one of the touchstones of the approach is that it aims at achieving a form of *practical stability*, before considering more stringent stability properties. In order to be a little more specific at the technical level, let us consider a controllable nonholonomic system whose governing kinematic equations are in the form $\dot{g} = \sum_{i=1}^m X_i(g)u_i$, with $m < n$, and $g \in \mathbb{R}^n$ denoting the state vector. Assume, to simplify, that the system's control vector fields (v.f.) X_i ($i \in \{1, \dots, m\}$) generate a Lie algebra over \mathbb{R} of dimension n . The t.f. approach relies on the (proven [5][15]) existence of a bounded periodic n -dimensional vector-valued function $f(\theta)$, with θ belonging to the torus of dimension $(n - m)$, whose infinitesimal variation, at any point θ , is "transversal" to the directions given by the v.f. X_i evaluated at the point $f(\theta)$. This function can in turn be associated with a change of variables $(z, \theta) \triangleq \phi(g, \theta)$, $z \in \mathbb{R}^n$, such that z is all the more close to g than $|f(\theta)|$ is small, and such that, along the system's trajectories, the variation of z is given by an equation in the form $\dot{z} = H(g, \theta)v$, with H always invertible (thanks to the transversality property of f) and $v = (u_1, \dots, u_m, \dot{\theta}_1, \dots, \dot{\theta}_{n-m})^T$. By interpreting v as a n -dimensional control vector, the equation of variation of z is formally similar to the one of a fully actuated holonomic system with an equal number of control inputs and configuration variables to be controlled. Therefore, in a certain way, the t.f. approach allows the substitution of the initial nonholonomic system with state g by a "neighbor" holonomic system with state z .

An immediate application of this approach is the practical stabilization of an *arbitrary* reference trajectory, not necessarily realizable by the nonholonomic system. The method has been validated in simulation and experimentally on our laboratory mobile robot ANIS, with the task consisting in the vision-based tracking of an omnidirectional target/object by a unicycle-like mobile robot [19].

However, its adaptation to mobile manipulation is not direct because it also matters, beyond the practical stabilization objective, that the "hard" constraints imposed by the manipulation objective at the level of the manipulator's end-effector are respected. This difficulty, and our idea of coupling the t.f. control approach for nonholonomic systems with the task-function methodology used previously for controlling holonomic mobile manipulators—or with any other control design methodology used for holonomic manipulators—led us to introduce a notion of *equivalence* between a nonholonomic mobile manipulator and an omnidirectional one, *given a manipulation task*. This notion relies upon the existence of a change of coordinates which i) relates the state of the nonholonomic system to the "neighbor" state (in the sense of the t.f. approach) of a virtual omnidirectional system, and ii) leaves a certain number of constraint equations invariant so as to ensure that the perfect realization of the manipulation task by one of the two systems implies the same for the other system. A sufficient geometrical condition, for the existence of such a change of coordinates, has been pointed out. Once a virtual equivalent omnidirectional mobile manipulator has been defined, one is brought back to the easier problem (treated previously) of controlling such a system. The control law for the nonholonomic physical system can then be calculated, thanks to transversality of the function f used in the change of coordinates, from the one that one would use to control the virtual holonomic system. This method has been tested in simulation for a mobile manipulator with a unicycle-like base, and a task consisting in the end-effector's precise tracking of a spherical object observed via a camera mounted on the manipulator. Future developments will include:

- the treatment of a certain number of technical issues related to control implementation on a physical system,
- experimentation on our mobile manipulator ANIS,
- the adaptation and generalization of the method to other mechanical structures (mobile manipulators with a car-like base, for instance) and other robotic tasks.

6.1.3. Control of maneuvering car-like vehicles

We have worked on the adaptation of the t.f. control approach to car-like vehicles. These vehicles differ from unicycle-type ones by the existence of driving wheels used to change the vehicle's orientation when the longitudinal velocity is not equal to zero. The dimension of the corresponding kinematic model also increases from three to four. Beyond this increase of dimension, one of the difficulties of the adaptation is that the car's model, contrary to the unicycle's model, is not a system invariant on a Lie group. A possibility consists in transforming, via a local diffeomorphism upon the state and input variables, the car's model into the four-dimensional chained system which is invariant on a Lie group. The limitations of this approach come, on the one hand, from the complications associated with the change of variables and, on the other hand, from the non-global character of the considered transformation. Another possibility, free of such limitations, consists in keeping the system's natural state and control variables and using the transformation towards the four-dimensional chained system only at the level of the transverse function. This way of proceeding preserves the possibility of using the homogeneity property of the chained systems for setting the parameters of the transverse function, and has allowed us to derive globally stabilizing feedback controls for the car. The practical interest of the method is complemented by the conceptual result of a system which, although it is not invariant on a Lie group, can be globally stabilized (in the practical stabilization sense) by application of the t.f. approach.

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

We have further pursued the study of the problem of tracking a moving target by a nonholonomic unicycle-type vehicle equipped with a camera. Last year's results, on the observation of the relative vehicle/target posture and estimation of the target's velocity, have been collected in a technical report [29] and a conference communication [19]. Another aspect of the study concerns the monitoring of the convergence transient behavior when the vehicle is initially far away from its desired position/orientation (with respect to the target), or when a tracking mismatch occurs at some point (resulting, for example, from control saturations or control discretization when maneuvers would require fast abrupt changes in the control inputs). The principle of the proposed method is to use the degrees of freedom of the control so as to minimize at every time-instant the norm of the control vector (whose components include the longitudinal and angular velocities of the vehicle's body) under the constraint of ensuring a pre-defined rate of convergence to zero (uniformly exponential, for instance) for the norm of the tracking error vector. Simulation results show that this method tends to produce transient trajectories that involve a small number of intermediary maneuvers.

6.1.5. Field-oriented control of induction motors

Field-oriented control is a well established method for controlling highly nonlinear induction motors. By using the structural "parenthood" of induction motors equations and the generalized nonholonomic integrator (itself globally equivalent to the three-dimensional chained system), and in particular the underlying Lie group invariance property of these systems, we have shown how, in contrast with classical input-output and dynamic feedback stabilization techniques, singularity-free versions of the field-oriented control method can be obtained by direct application of the t.f. control approach. In our opinion this is a good illustration of the generality of this approach and its relevancy for addressing various control applications. This result has been reported in a conference communication [25].

6.2. Mobile robot navigation and guidance

Participants: Patrick Rives, Jean-Jacques Borrelly, Alessandro Corrêa-Victorino, Nicolas Simond.

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

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 group, 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. 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 axis 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 onboard weakly calibrated stereovision system.

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

We are interested in controlling the motion of a robot during its navigation in an indoor environment so that the obstacles are avoided and the robot can access the whole free space during its exploration task. The Voronoï diagram (VD), already used by several authors, is a tool well adapted to support navigation tasks. For instance, it satisfies the following properties:

- it can be locally calculated for each position of the robot,
- it belongs, by construction, to the free space,
- following its branches allows for a complete exploration of the environment,
- it captures the topology and accessibility of the robot’s environment.

In terms of navigation tasks, moving on a Voronoï branch can be viewed as a natural way to join two different locations in an indoor environment. Complete exploration of an indoor environment can be performed by making the robot move on the VD, using the three following navigation tasks :

- reach the nearest Voronoï branch from any point of the free space and align the robot longitudinal axis with it,
- move along a Voronoï branch,
- stop the robot at a Voronoï bifurcation point.

Using the sensor-based control formalism developed in the Icare group, adapted to the laser range data, we have designed feedback control laws capable of implementing such navigation tasks robustly. An analysis has allowed us to derive sufficient conditions for stability and robustness of the control laws against modeling errors concerning the robot’s dynamics and noisy measurements issued from the laser.

As for the localization and mapping processes, it is now well known that the quality of the results is highly dependent on the accuracy of the dead reckoning method used to estimate the robot motion. To overpass the problem of drift occurring with the classical odometry based on wheels' encoders, we have developed a new method based on the use of the laser range data. Thanks to the observability rank condition theorem, we have proved that for certain configurations of the local environment surrounding the robot, its motion is not fully observable from the laser data only. In this case, we use additional information obtained by projecting the odometry data computed from the wheels' encoders onto the non-observed direction. In the figure 1, the positions estimated from the wheels' encoders are represented by crosses, and those given by the estimation method based on laser range data are marked by circles. One can see that the robot's position estimated from the odometry data diverges considerably from the robot's real position after a few cycles, whereas the position estimated with our method matches the real position of the robot in the environment perfectly. The uncertainties associated with the estimated positions are represented by the ellipses.

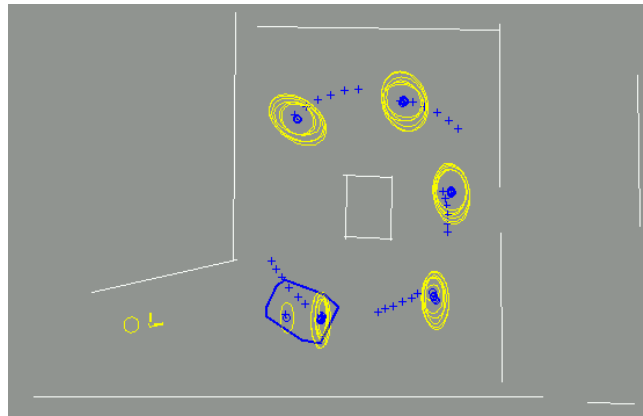


Figure 1. Dead reckoning based on laser range data versus odometry from wheels encoders

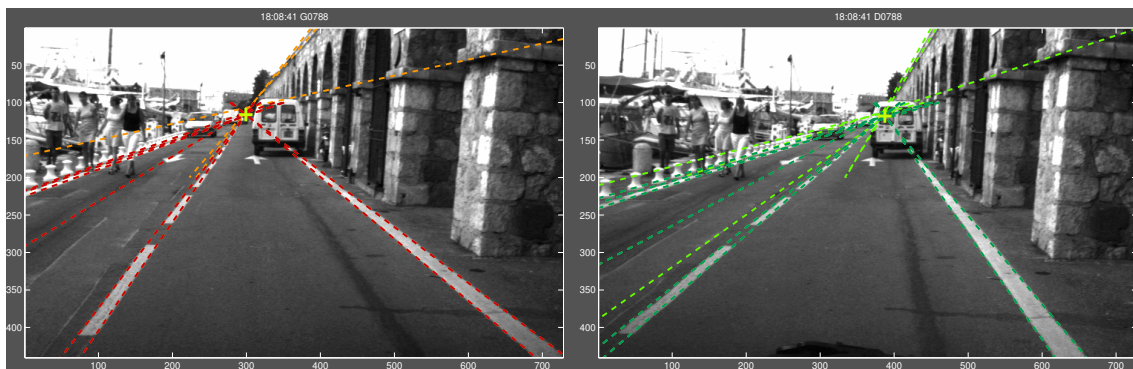
Another contribution to the SLAM problem concerns the incremental building of a hybrid model of the environment that mixes topological and geometrical aspects for navigation purposes. Our approach is based, in part, on a method presented by Kuipers in [35], and also on the methodology presented by Choset in [31]. It is based on Kuipers's method in the sense that the topological description of the environment is constructed in an autonomous way relying upon a sensor-based navigation strategy. It is based on the Choset's methodology in the sense that the robot is constrained to move on the Voronoï diagram of the environment during the exploration phase. As an improvement of these previous works, we propose to construct the geometric and topological models simultaneously in an incremental way along the exploration of the environment. During this phase the robot constructs a graph representation which determines the accessibility of the free space. At the same time, a geometrical representation is also incrementally built and updated in parallel with the construction of the topological model. To overpass the problems of matching that occur in large scale environments when the robot crosses again a region already explored, we introduce a hierarchy in the model of the environment in terms of locations and access linkages. Each location is defined as a set of rigid geometrical primitives expressed in a local frame. The access linkages between the different locations are represented by stretchable strips. The global model of the environment is built using an optimization technique inspired from the *snake* technique used in vision.

The complete methodology has been successfully validated on our experimental mobile robot ANIS and published in the *International Journal of Robotics Research* [17], [18]. It will be extended in the context of the *Programme d'Etude Amont: MiniROC* funded by the *DGA (Délégation Générale à l'Armement)* in which the Icare team is in charge of the localization and the mapping workpackages.

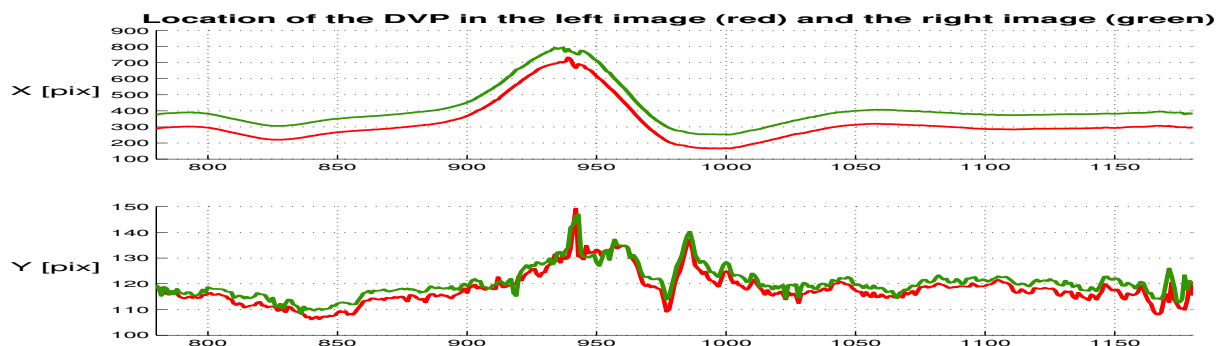
6.2.2. Accurate localization of a car-like vehicle in an urban environment

Assuming that the urban scene contains planar structures, the computation of the homography between two images fully characterizes the camera displacement in the projective space. An important work effort has been devoted this year to the development of a robust approach for computing such a homography by using points and lines painted on the road. Our approach is based on the detection of the dominant vanishing point (DVP) and of the vanishing lines (VLs) used to delimit road strips. In a classical manner we use a Canny edge detector to extract the contours in the image and compute an approximation of the DVP's position in the current image. From a robust tracker applied to the sequence of images, we are able to get a current estimate which allows us to compute a coarse segmentation of the road in the image. Using the Harris points of interest detected in the region of the image corresponding to the road and VLs, we are able to compute the homography between two different images in the sequence.

The methodology has been validated on sequences of images recorded in the old city of Antibes. An example of DVP and VLs estimation is shown in the figure 2-a. The figure 2-b illustrates the quality of the tracking of the DVP along the sequence of images.



(a) DVP and VL detection in the images



(b) Tracking of the DVP along the sequence

Figure 2. Segmentation of the road

6.3. Uncalibrated visual servoing in unknown environments

Participants: Ezio Malis, Patrick Rives, Jean-Jacques Borrelly, Selim Benhimane.

Key words: *visual servoing, active vision, dynamic vision, robust vision algorithms.*

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's 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.
- 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.

6.3.1. Vision-based control using a zooming camera

Our research work on this topic corresponds to our participation in the AEROB project within the ROBEA program funded by CNRS and INRIA. In order to carry on robotic tasks autonomously, it is commonly accepted that vision sensors and associated control techniques have a major role to play. Visual servoing is an efficient method to control robots in unknown and dynamically changing environments. A typical robotic task consists in positioning an eye-in-hand system with respect to an observed object. Many methods have been proposed in the last few years to perform this task. Among the different techniques that have been developed, those most often used are based on the "teaching-by-showing" approach. The principle is the following. The camera mounted on the robot is first placed at a location corresponding to the desired position of the robot with respect to some target object, and a reference image characterizing this location is stored in memory. When starting from another position, with the target still in the field of view of the camera, the robot is controlled so as to have the current and reference images coincide. For this approach to work, the camera's intrinsic parameters have to be the same as when the reference image was taken. Indeed, in the case where these proprioceptive parameters vary during the servoing phase, or if the camera used for the servoing is different from the one used to acquire the reference image, the coincidence of images evoked above does no longer imply that the robot is driven back to the desired position. The constraining assumption of working with identical and constant camera intrinsic parameters (including the focal length) represents a limitation for the applicability of the visual servoing approach. Zooming mechanisms are useful to alleviate this type of limitation. Many studies have proved that zooming while doing servo-control presents many advantages because the precision with which the positioning task is performed, and the accuracy of the primitive extraction process, are highly correlated with the resolution of the image. Standard visual control techniques that use zooming during the control of the robot do not permit the positioning of the camera independently of the camera intrinsic parameters. Some of them require the knowledge of a model of the target, or at least partial information about it, in order to control the camera's focal length. In a recent work [22] we have shown that it is possible to position a camera (whose intrinsic parameters may vary) with respect to a *non-planar* object by using a reference image taken with a different camera. Unfortunately, the proposed method does not work when the target is planar. One of our objectives, this year, was to eliminate the constraining assumption of non-planarity so as to increase

the versatility of visual servoing techniques and enlarge their domain of application [21]. A visual servoing controller, insensitive to variations of the camera intrinsic parameters, and not relying upon the planarity of the target, has been proposed. A complementary result is a focal length control strategy which allows to maintain the target within the field of view of the camera during the control phase and recover the focal length value associated with the reference image without any preliminary information about it. The proposed method has been successfully tested experimentally.

6.3.2. Robustness of image-based visual servoing

Unlike model-based visual servoing methods, image-based visual servoing does not rely upon the knowledge of a complete model of the target. On the other hand, information about the depth coordinate of the object in the camera frame must be provided. It is known, by experience, that a rough approximation of the depth distribution is sufficient to ensure the stability of the control law. However, when the environment is completely unknown and the robot is uncalibrated, the stability of the visual servoing in the presence of depth estimation errors can become a serious issue. We have tried to identify and analyze the source of robustness of image-based visual servoing methods w.r.t. calibration errors. Due to the complexity of the problem few theoretical results have been obtained concerning stability. The theoretical analysis has been carried out in very simple cases only, often by considering a simplified model for the camera intrinsic parameters, and always assuming that the depth distribution was perfectly estimated. In [23] we have studied the robustness of the image-based visual servoing method with respect to errors upon the depth distribution. The analysis proposed in the paper is not limited to purely image-based visual servoing methods. It can be extended to recent invariant methods which use several image-based features in the control law. We have shown that extreme care must be taken when approximating the depth distribution of a target for image-based visual servoing. The reason is that the stability region in the presence of errors on the depth distribution is not very large. As a consequence, if the target geometry is completely unknown then an accurate estimation of the depth coordinate is necessary. Accordingly, a continuation of this work has been devoted to the off-line estimation of the depth distribution with a precision as specified by the sufficient stability conditions given in the paper.

6.3.3. Uncalibrated active affine reconstruction

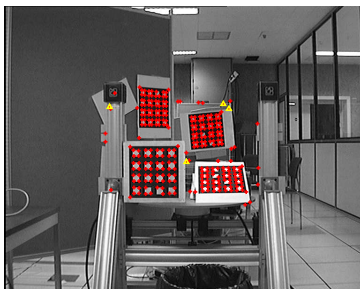
Many vision-based control schemes use some a priori knowledge about the geometry of the environment. For example, in order to implement an image-based visual servoing using image points as visual features, one needs to know the depth coordinates of these points (i.e. the depth distribution). Even though direct measurement of depth coordinates is usually not available in images, these coordinates can be estimated. It has been shown in [24] that estimation errors on the depth distribution can make the vision-based control unstable. The identification of the minimal information needed to implement a vision-based control law in a stable manner allows to focus and restrict the estimation effort. Affine reconstruction is a possible way to address this type of issue because it allows to recover the depth distribution of a set of points by relying upon weaker assumptions on the system than in the case of full Euclidean reconstruction. In the first place, accurate calibration of the robot and/or camera is not required. Then, only two images containing the considered set of points are sufficient to perform the depth distribution estimation. Now, it is well known that affine reconstruction from perspective image pairs is an easy task when the displacement of the camera between the two images is a pure translation. The direction and distance of this translation can be arbitrary and unknown. A pure translation motion via open-loop control is possible only when the robot manipulator on which the camera is mounted is well calibrated. By contrast, we propose an active affine reconstruction method for which the pure translation motion is performed by closing the loop with a visual servoing technique. In this case, accurate calibration of the robot and the camera is not required, and a precise model of the environment is not needed either. Epipolar geometry constraints can be used as proposed in [10]. The key idea is to define constraints that the considered points in the final image must satisfy in order to allow for a pure translation motion between the initial and final images. However, the visual servoing method proposed in [10] cannot be used as such because it assumes that the depth distribution is known. We use instead the 2 1/2 D visual servoing method [3] which does not rely on this knowledge. The visual servoing task is then performed without any model of the object and any reference image. Only the current and initial images are used to control the camera. Once the

pure translation motion is performed the affine reconstruction is straightforward. The depth coordinates of the points in the scene are estimated once for all. They can subsequently be used either in other visual servoing schemes which depend on them or to perform full 3D reconstruction of the scene.

6.3.4. Matching points with different image resolutions

Our research work on this topic corresponds to our participation in the AEROB project within the ROBEA program. One of the project's goals is to localize a robot in a model of the environment, built beforehand, by matching feature points in an image acquired by an on-board camera with corresponding points in the model.

In [20] we have proposed a new method for matching points between two images at different resolutions using characteristic quantities (called “invariants” in what follows) which do not depend on the camera intrinsic parameters. One of the images is acquired with a given set of camera parameters, while the second one is acquired from the same position, but with different camera parameters. If the feature points are correctly matched between the two images, the invariants computed from the two images are equal. A difference in the invariants implies that some of the points are mismatched. Accordingly, we discard points which do not match well until the computed invariants are closest to each other. The proposed matching method has been tested on real images with very good results. Three examples are shown in Figure 3. The feature points are obtained by using a modified Harris corner detector. In spite of the important discrepancy in the resolution, all red points are well matched. Only a few yellow points are not correctly matched.



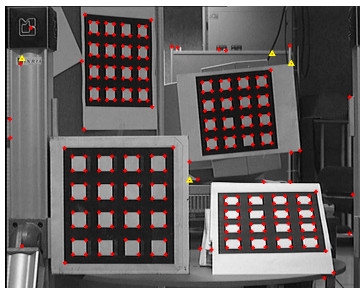
(a)Image 1 low resolution



(b)Image 2 low resolution



(c)Image 3 low resolution



(d)Image 1 high resolution



(e)Image 2 high resolution



(f)Image 3 high resolution

Figure 3. Matching points at different resolutions by using invariants.

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

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)].

Key words: *aerial unmanned vehicle, aerodynamical modeling, sensor-based control, visual servoing.*

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). Practically, the autopilots currently in use 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 [6], we designed a LQR controller based on a time-varying linearized model, computed on line and parametrized by the air velocity and the altitude. We have applied a similar approach to derive visual servoing control schemes using an onboard 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) [27].

Our research interest, this year, 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 (river) is modelled 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 controlling 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. With an airborne camera whose optical axis is aligned with the longitudinal axis of the airship, the image is composed of two main zones featuring the sky, in the upper part of the image, and the landscape, in the lower part. The line which separates these two zones - the horizon line - belongs to the plane at infinity and is, for this reason, a good candidate for the visual signals. The set of lines in the image plane defines a manifold of dimension two. Therefore, at most two rotations (tilt and roll) can be controlled from the horizon line parameters. The remaining rotation (pan) is controlled via the definition of the road following task. Due to the projective model of the camera, the two lines l_1 and l_2 (corresponding to the projections of L_1 and L_2 in the image) cross each other in the image at the so-called vanishing point. This point is located on the horizon line and belongs to the plane at infinity. Subsequently, its motion in the image depends only on the camera's rotation. Finally, using the horizon line parameters and the coordinates of the vanishing point in the image, we obtain four visual signals which can be used to control the three rotation degrees of freedom of the camera. In practice, we have chosen to use the x and y coordinates of the vanishing point and the angle of the horizon line w.r.t. the image frame. Concerning the control of the camera's position, we use a combination of the parameters of the lines l_1 and l_2 in order to get good decoupling properties for the lateral and vertical motions. The altitude and the lateral translation motion are controlled by using $(\theta_{l_1} + \theta_{l_2})/2$ and $(\theta_{l_1} - \theta_{l_2})/2$ respectively. Unfortunately, these two visual signals depend also on the camera's orientation. Finally, an image-based visual servoing controller is derived by using a LQR technique.

We consider a linearized model which takes both the model of the airship and the model of the vision process into account via the image Jacobian matrix corresponding to the situation where the airship is aligned with the road. By using the visual signals as defined above we obtain, at the desired position, an upper triangular Jacobian matrix which yields good decoupling properties.

The figure 4 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.

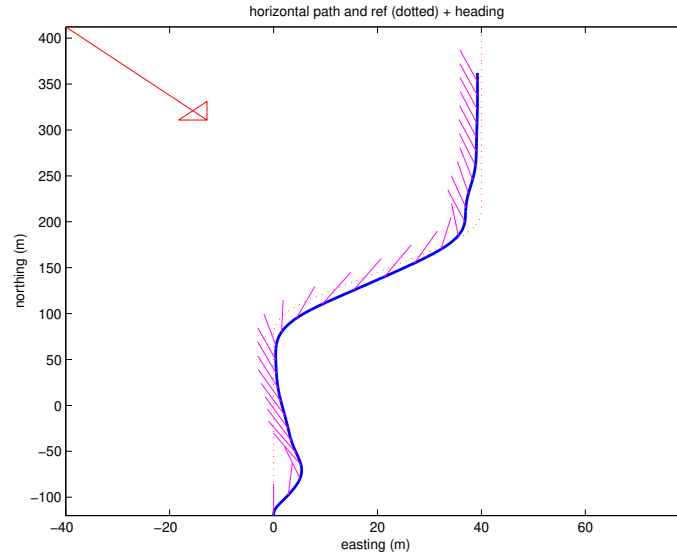


Figure 4. A road following task with strong lateral wind

7. Contracts and Grants with Industry

7.1. Project IST CyberCars

Key words: *Urban vehicles, navigation, control.*

Participants: Guillaume Artus, Nicolas Simond, Jean-Jacques Borrelly, 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).

8. Other Grants and Activities

8.1. National Activities

8.1.1. RTP « Systèmes Aérospatiaux » (CNRS)

Participant: Patrick Rives.

P. Rives is a member of the “steering committee” of the RÉSEAU THÉMATIQUE « SYSTÈMES AÉROSPATIAUX » CNRS.

8.1.2. CNRS research projects ROBEA

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

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

- *Ground and aerial mobile robots in outdoor environments: environment modeling and safe vision-based navigation*
- *Control of non-holonomic mobile manipulators*

These projects are led in collaboration with university and CNRS research teams: LAAS (Toulouse), ENI (Tarbes), LSIIT (Strasbourg), CESBIO (Toulouse). They have been launched in the fall of 2001 for a duration of three years.

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 will spend part of his sabbatical year with the Icare research group. The subject of research is 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

G. F. Silveira, from the Robotics and Vision Lab at CenPRA (Campinas, Brazil) has visited us this year for two weeks. P. Rives has traveled to Campinas where he has worked for two weeks on the Aurora Project (see also the section *Joint research program INRIA/ICCTI* 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”.

9.2. International conferences

Icare's researchers have presented works at the following conferences:

- IEEE International Conference on Robotics and Automation, Taipei, Taiwan, September 2003.
- IEEE Conference on Advanced Robotics, Coimbra, Portugal, July 2003.
- IEEE/RSJ International Conference on Intelligent Robots Systems, Las Vegas, USA, October 2003.
- IEEE Conference on Decision and Control, Hawaii, USA, December 2003.

9.3. Award

E. Malis and F. Chaumette (member of the Vista project-team at INRIA Rennes) have been awarded the 2002 K.S. Fu Best Transactions Paper Award for their paper entitled "Theoretical Improvements in the Stability Analysis of a New Class of Model-Free Visual Servoing Methods", (pp.176-186, April 2002). The award was presented on September 17, 2003 at ICRA2003 by Peter Luh, Editor-in-chief of IEEE Transactions in Robotics and Automation.

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 at the head of the R&D action VISA aimed to develop the applications in the field of the Intelligent Transport System (ITS).

9.5. Education Through Research

- *Current Research Students* :
 - G. Artus, « Automatisation de manœuvres pour une voiture électrique », École des Mines de Paris, supervisors : C. Samson, P. Morin.
 - S. Benhimane, « Asservissement visuel avec une optique à focale variable », supervisors : P. Rives, E. Malis.
 - 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.
- *Participation to Ph.D. committies* :
 - P. Rives has participated in five Phd defense juries and one HDR (Habilitation à Diriger les Recherches) jury.
- *Training periods* :
 - N. Garcia, "Preserving the continuity of the task function during tracking a sequence of features in a wide environment", 3 months, supervisor : E Malis.

9.6. Teaching

- P. Rives is member of the 61^e Commission de Spécialistes de l'Université de Nice - Sophia Antipolis.
- Lecture courses at the "École Nationale des Télécommunications de Bretagne": *Machine Vision* (P. Rives, 3 hours).
- Lecture courses at the "École des Mines de Paris", section "Automatique et Robotique": *Visual Servoing* (E. Malis, 6 hours).
- Lecture courses at the "École des Mines de Paris", section "Automatique et Robotique": *Sensor-based Control* (P. Rives, 6 hours).
- Lecture courses at the "École des Mines de Paris", section "Automatique et Robotique": *Introduction to control feedback of nonholomic systems* (P. Morin and G. Artus, 5 hours).

10. Bibliography

Major publications by the team in recent years

- [1] J.-J. BORRELLY, E. COSTE-MANIÈRE, B. ESPIAU, K. KAPellos, R. PISSARD-GIBOLLET, D. SIMON, N. TURRO. *The ORCCAD architecture*. in « International Journal of Robotics Research, MIT press », volume numéro spécial "Integrated Architectures for Robot Control and Programming", mars, 1998.
- [2] D. DJIAN, P. RIVES. *Reconnaissance d'objets 3D par vision active : Apprentissage de réseaux Bayésiens*. in « 11^{ème} Congrès AFCET RFIA », Clermont Ferrand, France, 19-21 janvier, 1998.
- [3] E. MALIS, F. CHAUMETTE, S. BOUDET. *2 1/2 D Visual Servoing*. in « IEEE Trans. on Robotics and Automation », number 2, volume 15, Avril, 1999, pages 234-246.
- [4] P. MORIN, J.-B. POMET, C. SAMSON. *Design of homogeneous time-varying stabilizing control laws for driftless controllable systems via oscillatory approximation of Lie brackets in closed-loop*. in « SIAM Journal of Control and Optimization », number 1, volume 38, 1999, pages 22-49.
- [5] P. MORIN, C. SAMSON. *A characterization of the Lie algebra rank condition by transverse periodic functions*. in « SIAM Journal of Control and Optimization », number 4, volume 40, 2001, pages 1227-1249.
- [6] P. RIVES, J. AZINHEIRA. *Visual Auto-landing of an Autonomous Aircraft*. Technical report, number 4606, INRIA, Nov 2002, <http://www.inria.fr/rrrt/rr-4606.html>.
- [7] P. RIVES, M. DEVY. *Perception pour la localisation*. J.-P. LAUMOND, editor, in « La robotique mobile », Hermes, 2001.
- [8] P. RIVES, M. DEVY. *Perception pour la navigation et la commande*. J.-P. LAUMOND, editor, in « La robotique mobile », Hermes, 2001.
- [9] P. RIVES, R. PISSARD-GIBOLLET, L. PELLETIER. *Sensor-based Tasks: From the Specification to the Control Aspects*. in « 6th Int. Symposium on Robotics and Manufacturing », Montpellier, France, 28-30 mai, 1996.
- [10] P. RIVES. *Visual Servoing Based on Epipolar Geometry*. in « IEEE Int. Conf. on Intelligent Robots and Systems », volume 1, pages 602-607, Takamatsu, Japan, Novembre, 2000.

- [11] C. SAMSON, M. LEBORGNE, B. ESPIAU. *Robot control. The Task Function approach*. series Oxford Engineering Series, volume 22, Oxford University Press, 1991.
- [12] C. SAMSON. *Velocity and torque feedback control of a nonholonomic cart*. in « Advanced Robot Control. Proceedings of the International Workshop on Nonlinear and Adaptive Control: Issues in Robotics, Grenoble, France, Nov. 21-23, 1990 », series Lecture Notes in Control and Information Sciences, volume 162, Springer-Verlag, pages 125-151, 1991, C. Canudas de Wit (Ed.).
- [13] C. SAMSON. *Control of chained systems. Application to path following and time-varying point stabilization of mobile robots*. in « IEEE Transactions on Automatic Control », number 1, volume 40, 1995, pages 64-77.

Articles in referred journals and book chapters

- [14] P. MORIN, C. SAMSON. *Practical and asymptotic stabilization of chained systems by the transverse function approach*. in « Siam J. on Control and Optimization », To appear.
- [15] P. MORIN, C. SAMSON. *Practical stabilization of driftless systems on Lie groups: the transverse function approach*. in « IEEE Trans. on Automatic Control », number 9, volume 48, 2003, pages 1496-1508.
- [16] P. MORIN, C. SAMSON. *Stabilisation des systèmes non linéaires sans dérive: l'approche par fonctions transverses*. in « Journal Européen des Systèmes Automatisés (JESA) », number 2, volume 37, 2003, pages 213-244.
- [17] A. VICTORINO, P. RIVES, J.-J. BORRELLY. *Safe Navigation for Indoor Mobile Robots, Part I: A Sensor-Based Navigation Framework*. in « Int. Journal of Robotics Research », number 12, volume 22, December 2003, pages 1005-1019.
- [18] A. VICTORINO, P. RIVES, J.-J. BORRELLY. *Safe Navigation for Indoor Mobile Robots, Part II: Exploration, Self-Localization and Map Building*. in « Int. Journal of Robotics Research », number 12, volume 22, December 2003, pages 1019-1041.

Publications in Conferences and Workshops

- [19] G. ARTUS, P. MORIN, C. SAMSON. *Tracking of an omnidirectional target with a nonholonomic mobile robot*. in « IEEE Conf. on Advanced Robotics (ICAR) », volume 3, pages 1468-1473, 2003.
- [20] S. BENHIMANE, E. MALIS. *Mise en correspondance d'images à différentes résolutions à l'aide d'invariants aux paramètres intrinsèques*. in « RFIA, to appear », January, 2004.
- [21] E. MALIS, S. BENHIMANE. *Vision-based control with respect to planar and non-planar objects using a zooming camera*. in « IEEE International Conference on Advanced Robotics », Coimbra, Portugal, July, 2003.
- [22] E. MALIS. *Vision-based control invariant to camera intrinsic parameters: stability analysis and path tracking*. in « IEEE International Conference on Robotics and Automation », volume 1, pages 217-222, Washington, D.C., USA, May, 2002.

- [23] E. MALIS, P. RIVES. *Robustness of Image-Based Visual Servoing with Respect to Depth Distribution Errors*. in « IEEE International Conference on Robotics and Automation », Taipei, Taiwan, May, 2003.
- [24] E. MALIS, P. RIVES. *Uncalibrated Active Affine Reconstruction closing the loop by Visual Servoing*. in « IEEE/RSJ International Conference on Intelligent Robots Systems », Las Vegas, USA, October, 2003.
- [25] P. MORIN, C. SAMSON. *Field-oriented control of induction motors by application of the transverse function control approach*. in « IEEE Conf. on Decision and Control », Hawaii, USA, december, 2003.
- [26] P. MORIN, C. SAMSON. *Practical and asymptotic stabilization of the 3D-chained system by the transverse function approach*. in « IEEE Conf. on Decision and Control », Hawaii, USA, december, 2003.
- [27] G. SILVEIRA, J. AZINHEIRA, P. RIVES, S. BUENO. *Line Following Visual Servoing for Aerial Robots Combined with Complementary Sensors*. in « IEEE International Conference on Advanced Robotics », Coimbra, Portugal, July, 2003.
- [28] N. SIMMOND, P. RIVES. *Homography from a Vanishing Point in Urban Scenes*. in « IEEE/RSJ International Conference on Intelligent Robots Systems », Las Vegas, USA, October, 2003.

Internal Reports

- [29] G. ARTUS, P. MORIN, C. SAMSON. *Tracking of an omnidirectional target with a unicycle-like robot: control design and experimental results*. Technical report, number 4849, INRIA, 2003, <http://www.inria.fr/rrrt/rr-4849.html>.
- [30] P. MORIN, C. SAMSON. *Practical and asymptotic stabilization of chained systems by the transverse function control approach*. Technical report, number 4712, INRIA, 2003, <http://www.inria.fr/rrrt/rr-4712.html>.

Bibliography in notes

- [31] H. CHOSET, K. NAGATANI. *Topological simultaneous localization and mapping (SLAM): toward exact localization without explicit localization*. in « IEEE Trans. on Robotics and Automation », number 2, volume 17, Avril, 2001, pages 125-137.
- [32] J.-M. CORON. *Global asymptotic stabilization for controllable systems without drift*. in « Mathematics of Control, Signals and Systems », volume 5, 1992, pages 295-312, New York: Springer-Verlag.
- [33] M. GHALLAB. *Planification et décision*. J.-P. LAUMOND, editor, in « La robotique mobile », Hermes, 2001.
- [34] T. HENDERSON, E. SHILCRAT. *Logical sensor systems*. in « Journal of Robotic Systems », number 2, volume 1, 1984, pages 169-193.
- [35] B. KUIPERS, Y. T. BYUN. *A robot exploration and mapping strategy based on semantic hierarchy of spatial representations*. in « Robotics and Autonomous Systems », number 1-2, volume 8, 1991, pages 47-63.
- [36] P. MORIN, C. SAMSON. *Practical stabilization of a class of nonlinear systems. Application to chain systems and mobile robots*. in « IEEE Conf. on Decision and Control », décembre, 2000.

-
- [37] P. RIVES. *Perception et contrôle d'exécution de tâches robotiques*. in « Journées Nationales de la Recherche en Robotique », Toulouse, France, novembre, 1997.
- [38] P. ROUCHON, M. FLIESS, J. LEVINE, P. MARTIN. *Flatness and motion planning: the car with -n- trailers*. in « Proc. Int. Conf. ECC'93 », Groningen, Holland, 1993.
- [39] C. SAMSON. *Développements récents et problèmes ouverts en commande de robots*. in « Journées Nationales de la Recherche en Robotique », Toulouse, France, novembre, 1997.
- [40] A. C. VICTORINO, P. RIVES, J. J. BORRELLY. *Localization and Map Building Using a Sensor-based Control Strategy*. in « IEEE Int. Conf. on Intelligent Robots and Systems, IROS2000 », Takamatsu, Japon, 1 - 3 novembre, 2000.