INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# Project-Team LAGADIC

# Visual servoing in robotics, computer vision, and augmented reality

## Rennes - Bretagne-Atlantique

Theme : Robotics

Activity Report

2009

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# 2. Overall Objectives

## 2.1. Overall Objectives

Research activities of the Lagadic team are concerned with visual servoing and active vision. Visual servoing consists in using the information provided by a vision sensor to control the movements of a dynamic system. This system can be real within the framework of robotics, or virtual within the framework of computer animation or augmented reality. This research topic is at the intersection of the fields of robotics, automatic control, and computer vision. These fields are the subject of profitable research since many years and are particularly interesting by their very broad scientific and application spectrum. Within this spectrum, we focus ourselves on the interaction between visual perception and action. This topic is significant because it provides an alternative to the traditional Perception-Decision-Action cycle. It is indeed possible to link more closely the perception and action aspects, by directly integrating the measurements provided by a vision sensor in closed loop control laws.

This set of themes of visual servoing is the central scientific topic of the Lagadic group. More generally, our objective is to design strategies of coupling perception and action from images for applications in robotics, computer vision, virtual reality and augmented reality.

This objective is significant, first of all because of the variety and the great number of potential applications to which can lead our work. Secondly, it is also significant to be able to raise the scientific aspects associated with these problems, namely modeling of visual features representing in an optimal way the interaction between action and perception, taking into account of complex environments and the specification of high level tasks. We also work to treat new problems provided by imagery systems such as those resulting from an omnidirectional vision sensor or echographic probes. We are finally interested in revisiting traditional problems in computer vision (3D localization, structure and motion) through the visual servoing approach.

# 3. Scientific Foundations

## 3.1. Visual servoing

Basically, visual servoing techniques consist in using the data provided by one or several cameras in order to control the motions of a dynamic system [3][4][7]. Such systems are usually robot arms, or mobile robots, but can also be virtual robots, or even a virtual camera. A large variety of positioning tasks, or mobile target tracking, can be implemented by controlling from one to all the degrees of freedom of the system. Whatever the sensor configuration, which can vary from one on-board camera on the robot end-effector to several free-standing cameras, a set of visual features has to be selected at best from the image measurements available, allowing to control the desired degrees of freedom. A control law has also to be designed so that these visual features $\mathbf{s}(t)$ reach a desired value $\mathbf{s}^*$, defining a correct realization of the task. A desired planned trajectory $\mathbf{s}^*(t)$ can also be tracked [13]. The control principle is thus to regulate to zero the error vector $\mathbf{s}(t) - \mathbf{s}^*(t)$ . With a vision sensor providing 2D measurements, potential visual features are numerous, since 2D data (coordinates of feature points in the image, moments [1], ...) as well as 3D data provided by a localization algorithm exploiting the extracted 2D features can be considered. It is also possible to combine 2D and 3D visual features to take the advantages of each approach while avoiding their respective drawbacks [9].

More precisely, a set $\mathbf{s}$ of $k$ visual features can be taken into account in a visual servoing scheme if it can be written:

$$\mathbf{s} = \mathbf{s}(\mathbf{x}(\mathbf{p}(t)), \mathbf{a}) \tag{1}$$

where $\mathbf{p}(t)$ describes the pose at the instant $t$ between the camera frame and the target frame, $\mathbf{x}$ the image measurements, and $\mathbf{a}$ a set of parameters encoding a potential additional knowledge, if available (such as for instance a coarse approximation of the camera calibration parameters, or the 3D model of the target in some cases).

The time variation of $\mathbf{s}$ can be linked to the relative instantaneous velocity $\mathbf{v}$ between the camera and the scene:

$$\dot{\mathbf{s}} = \frac{\partial \mathbf{s}}{\partial \mathbf{p}}\ \dot{\mathbf{p}} = \mathbf{L_s}\ \mathbf{v} \tag{2}$$

where $\mathbf{L_s}$ is the interaction matrix related to $\mathbf{s}$. This interaction matrix plays an essential role. Indeed, if we consider for instance an eye-in-hand system and the camera velocity as input of the robot controller, we obtain when the control law is designed to try to obtain an exponential decoupled decrease of the error:

$$\mathbf{v}_c = -\lambda \widehat{\mathbf{L_s}}^+ (\mathbf{s} - \mathbf{s}^*) - \widehat{\mathbf{L_s}}^+ \widehat{\frac{\partial \mathbf{s}}{\partial t}} \tag{3}$$

where $\lambda$ is a proportional gain that has to be tuned to minimize the time-to-convergence, $\widehat{\mathbf{L_s}}^+$ is the pseudo-inverse of a model or an approximation of the interaction matrix, and $\widehat{\frac{\partial \mathbf{s}}{\partial t}}$ an estimation of the features velocity due to a possible own object motion.

From the selected visual features and the corresponding interaction matrix, the behavior of the system will have particular properties as for stability, robustness with respect to noise or to calibration errors, robot 3D trajectory, etc. Usually, the interaction matrix is composed of highly non linear terms and does not present any decoupling properties. This is generally the case when $\mathbf{s}$ is directly chosen as $\mathbf{x}$. In some cases, it may lead to inadequate robot trajectories or even motions impossible to realize, local minimum, tasks singularities, etc. [2]. It is thus extremely important to design adequate visual features for each robot task or application, the ideal case (very difficult to obtain) being when the corresponding interaction matrix is constant, leading to a simple linear control system. To conclude in few words, **visual servoing is basically a non linear control problem. Our Holy Grail quest is to transform it to a linear control problem.**

Furthermore, embedding visual servoing in the task function approach allows solving efficiently the redundancy problems that appear when the visual task does not constrain all the degrees of freedom of the system [7]. It is then possible to realize simultaneously the visual task and secondary tasks such as visual inspection, or joint limits or singularities avoidance. This formalism can also be used for tasks sequencing purposes in order to deal with high level complex applications [10].

## 3.2. Visual tracking

Elaboration of object tracking algorithms in image sequences is an important issue for researches and applications related to visual servoing and more generally for robot vision. A robust extraction and real-time spatio-temporal tracking process of visual cues is indeed one of the keys to success of a visual servoing task. To consider visual servoing within large scale applications, it is mandatory to handle natural scenes without any fiducial markers but with complex objects in various illumination conditions. If fiducial markers may still be useful to validate theoretical aspects of visual servoing in modeling and control, non cooperative objects have to be considered to address realistic applications.

Most of the available tracking methods can be divided into two main classes: feature-based and model-based. The former approach focuses on tracking 2D features such as geometrical primitives (points, segments, circles,...), object contours, regions of interest...The latter explicitly uses a model of the tracked objects. This can be either a 3D model or a 2D template of the object. This second class of methods usually provides a more robust solution. Indeed, the main advantage of the model-based methods is that the knowledge about the scene allows improving tracking robustness and performance, by being able to predict hidden movements of the object, detect partial occlusions and acts to reduce the effects of outliers. The challenge is to build algorithms that are fast and robust enough to meet our applications requirements. Therefore, even if we still consider 2D features tracking in some cases, our researches mainly focus on real-time 3D model-based tracking, since these approaches are very accurate, robust, and well adapted to any class of visual servoing schemes. Furthermore, they also meet the requirements of other classes of application, such as augmented reality.

# 4. Application Domains

## 4.1. Panorama

The natural applications of our research are obviously in robotics. In the past, we mainly worked in the following fields:

- grasping and manipulating tools in hostile environments such as nuclear environment typically;
- underwater robotics for the stabilization of images and the positioning of uninstrumented robot arm;
- agro-industry for the positioning of a vision sensor in order to ensure an improvement of the quality controls of agro-alimentary products; and
- video surveillance by the control of the movements of a pan-tilt camera to track mobile natural objects.

More recently, we addressed the field of mobile robotics through activities around the Cycab vehicle (see Section 5.6): detection and tracking of mobile objects (pedestrians, other vehicles), control by visual servoing of the movements of the vehicle.

In fact, researches undertaken in the Lagadic group can apply to all the fields of robotics implying a vision sensor. They are indeed conceived to be independent of the system considered (and the robot and the vision sensor can even be virtual for some applications).

Currently, we are interested in using visual servoing for robot arms in space, micromanipulation, autonomous vehicle navigation in large urban environments, and underactuated flying robots such as miniature helicopters and aircrafts.

We also address the field of medical robotics. The applications we consider turn around new functionalities of assistance to the clinician during a medical examination: visual servoing on echographic images, active perception for the optimal generation of 3D echographic images, compensation of organ motions, etc.

Robotics is not the only possible application field to our researches. In the past, we were interested in applying visual servoing in computer animation, either for controlling the motions of virtual humanoids according to their pseudo-perception, or for controlling the point of view of visual restitution of an animation. In both cases, potential applications are in the field of virtual reality, for example for the realization of video games, or virtual cinematography.

Applications also exist in computer vision and augmented reality. It is then a question of carrying out a virtual visual servoing for the 3D localization of a tool with respect to the vision sensor, or for the estimation of its 3D motion. This field of application is very promising, because it is in full rise for the realization of special effects in the multi-media field or for the design and the inspection of objects manufactured in the industrial world.

Lastly, our work in visual servoing and active perception could be related with those carried out in cognitive science, in particular in the field of psychovision (for example on the study of eye motion in the animal and human visual system, on the study of the representation of perception, or on the study of the links between action and perception).

# 5. Software

## 5.1. ViSP: a visual servoing platform

**Participants:** Fabien Spindler, Éric Marchand, Nicolas Melchior.

Visual servoing is a very active research area in robotics. A software environment that allows fast prototyping of visual servoing tasks is then of prime interest. The main difficulty is that it usually requires specific hardware (the robot and, most of the time, dedicated image framegrabbers). The consequence is that the resulting applications are often not portable and cannot be easily adapted to other environments. Today's software design allows proposing elementary components that can be combined to build portable high-level applications. Furthermore, the increasing speed of micro-processors allows developing real-time image processing algorithms on an usual workstation. We have thus developed a library of canonical vision-based tasks for eye-in-hand and eye-to-hand visual servoing that contains the most classical visual features that are used in practice. The ViSP software environment features all the following capabilities: independence with respect to the hardware, simplicity, extendability, portability. Moreover, ViSP involves a large library of elementary positioning tasks with respect to various basic visual features (points, straight lines, circles, spheres, cylinders, frames, ...) that can be combined together, and an image processing library that allows tracking of visual cues (dots, segments, ellipses,...). Simulation capabilities are also available. ViSP and its full functionalities are presented Fig. 1 and described in [12].

This year, we continued to improve the software and documentation quality. A new open source version was released in April. It is available at http://www.irisa.fr/lagadic/visp/visp.html.

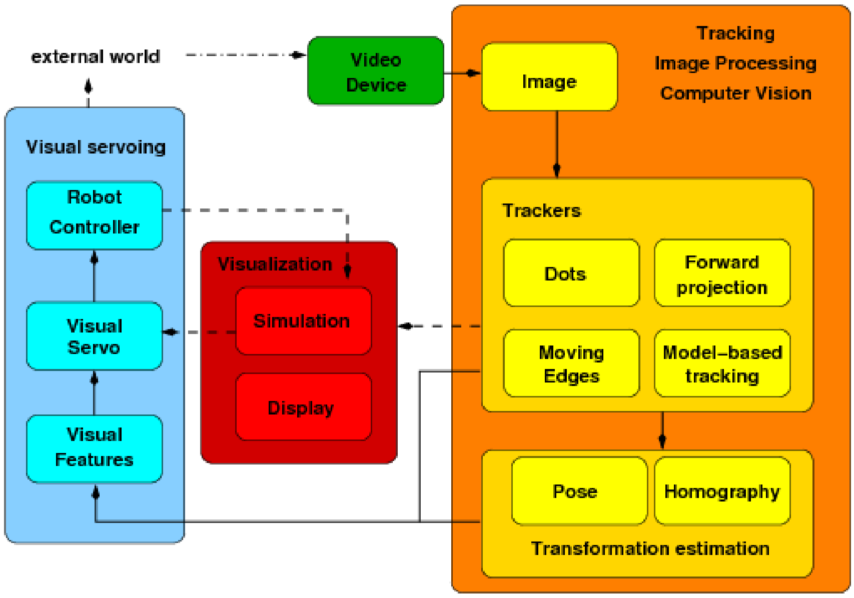



*Figure 1. ViSP software architecture.*

To ensure the stability of the software, daily builds were tighten on Inria's porting platform (Pipol) to test ViSP on new materials but also different software architectures (Linux, Windows, Mac OS). Moreover, new functionnalities were introduced like new visual servoing features, linear Kalman filtering, tracking of curves modelized by NURBS, control of the Adept Viper robot, real-time data plotting. A new release is planed in December.

ViSP last open source release code has been downloaded more than 360 times in 2009. It is used in research labs in France, USA, Japan, Korea, India, China, Lebanon, Italy, Spain, Portugal, Hungary and more recently Canada. For instance, it is used as a support in a graduate course delivered at MIT and at IFMA Clermont-Ferrand engineer school.

## 5.2. Marker: Marker-based augmented reality kernel

**Participant:** Éric Marchand.

The Marker software implements an algorithm supplying the computation of camera pose and camera calibration using fiducial markers. The parameters estimation is handled using virtual visual servoing. The principle consists in considering the pose and the calibration as a dual problem of visual servoing. This method presents many advantages: similar accuracy as for the usual non-linear minimization methods, simplicity, effectiveness. A licence of this software was yielded to the Total Immersion company.

## 5.3. MarkerLess: MarkerLess-based augmented reality kernel

**Participant:** Éric Marchand.

Markerless is an upgrade of the Marker software with additional features developed within the SORA Riam Project. It allows the computation of camera pose with no fiducial marker.

A real-time, robust and efficient 3D model-based tracking algorithm for a monocular vision system has been developed [5]. Tracking objects in the scene requires to compute the pose between the camera and the objects. Non-linear pose computation is formulated by means of a virtual visual servoing approach. In this context, the derivation of point-to-curves interaction matrices have been obtained for different features including straight lines, circles, cylinders and spheres. A local moving-edge tracker is used in order to provide a real-time estimation of the displacements normal to the object contours. A method has been proposed for combining local position uncertainty and global pose uncertainty in an efficient and accurate way by propagating uncertainty. Robustness is obtained by integrating an M-estimator into the visual control law via an iteratively re-weighted least squares implementation. We also considered the case of non-rigid articulated objects. The proposed method has been validated on several complex image sequences including outdoor environments. Applications for this tracker are in the fields of robotics, visual servoing, and augmented reality.

## 5.4. Development work: Robot vision platforms

**Participants:** Fabien Spindler, Romain Tallonneau.

We exploit several experimental platforms to validate our researches in visual servoing and active vision. More precisely, we have two industrial robotic systems built by Afma Robots in the nineties. The first one is a Gantry robot with six degrees of freedom, the other one is a cylindrical robot with four degrees of freedom (see Fig. 2a). These robots are equipped with cameras mounted on their end effector. These equipments require specific hardware, but also software maintenance actions and new developments in order to make them evolve. Training and assistance of the users, presentation of demonstrations also form part of the daily activities.

This year, two new pneumatic grippers, a vaccum and two parallel fingers gripper, were interfaced with the end-effector Gantry robot. These new accessories allow to develop and validate several algorithms developped for the ANR Psirob RobM@rket project (see Section 8.2.5).

Since October, to improve the panel of demonstrations and to highlight our research activities we are developing new robotic vision-based applications. We started by using model-based visual tracking techniques to show how it is possible to combine them in order to pick up and manipulate objects.

This platform is by far the most-used one by Lagadic members (6 papers published in 2009 enclose results validated on it). This year, it was also opened and used by a group of assistant professors and students from the INSA Rennes engineer school for calibration issues.

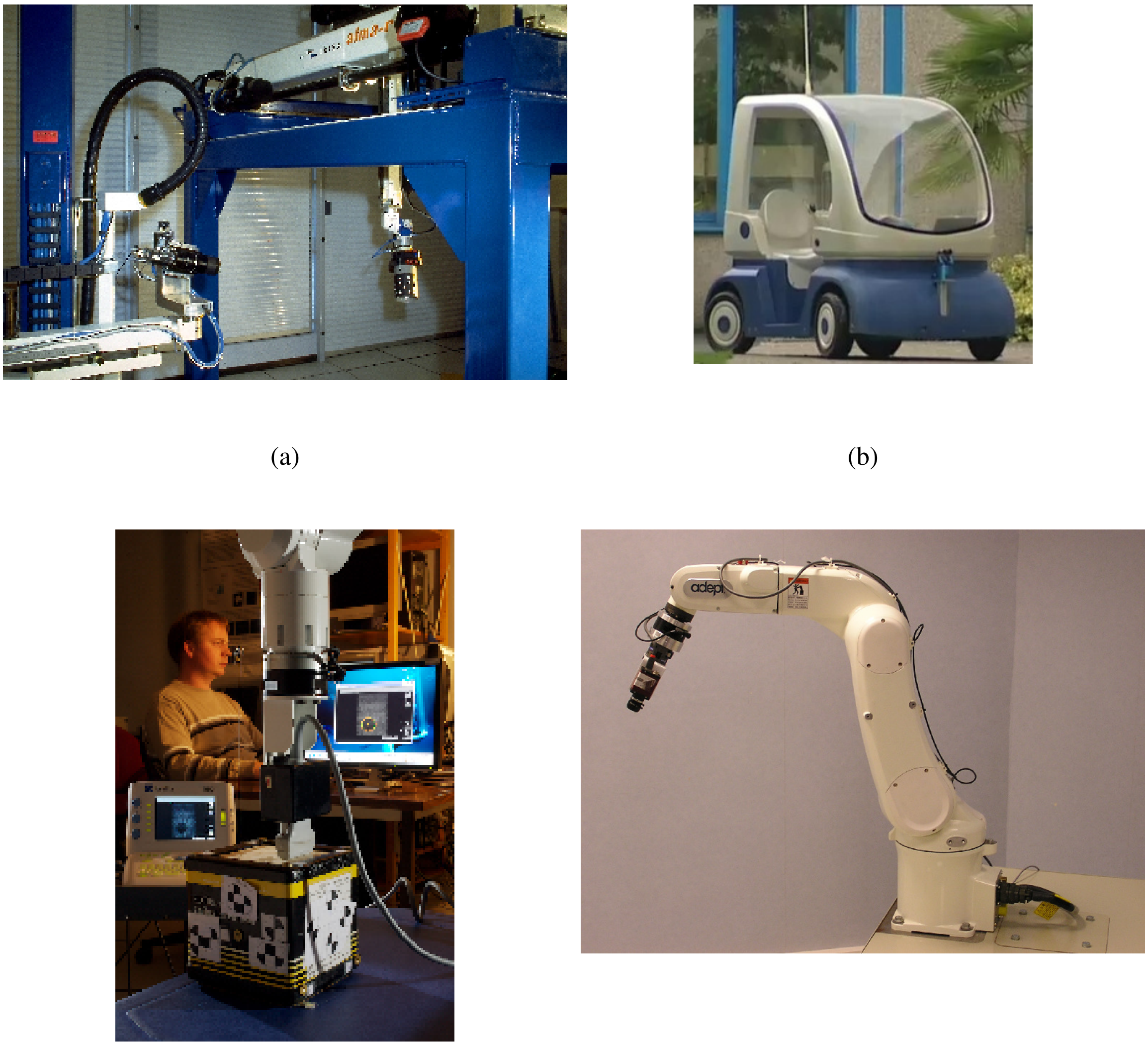
## 5.5. Development work: Medical robotics platforms

**Participants:** Fabien Spindler, Alexandre Krupa.

To validate our researches in medical robotics, we exploit since 2004 a six degrees of freedom Hippocrate medical arm designed by the Sinters company (see Fig. 2.c). A force torque sensor is mounted on the end-effector holding an ultrasound probe connected to a SonoSite 180 Plus imaging system. A PC running Linux is used for image processing and for controlling the low level controller under QNX via a LAN network. This material is shared betweeen the Lagadic and Visages teams.

In order to improve visual servoing techniques using ultrasound images, a next step is to take into account physiological motion of organs, for example deformations due to the breathing. Therefore it is essential to first simulate and control this motion that is considered as a pertubation by using an experimental setup providing ground truth. As part of this new setup, a new Adept Viper S850 arm was installed in September (see Fig. 2.d). New software developments were done to interface this robot in our visual servoing platform ViSP (see Section 5.1). It will allow applying a periodical rigid motion to an artifical soft tissue phantom. This new robot will also be used to validate experimentally the research done in the ANR Prosit project (see Section 8.2.6) before the transfer to the project partners.

As described in Section 6.2.1, visual servoing methods using ultrasound images have been improved. The platform was used to validate the automatic positioning of a 2D US probe in order to reach a desired B-scan image of an object of interest. It was also used to extend and validate the motion tracking approach using ultrasound speckle [19].



(a) (b)

(c) (d)

*Figure 2. Lagadic robotics platforms: a) cylindrical robot on the left and Gantry robot on the right, b) Cycab vehicle, c) Hippocrate medical robot, d) Viper robot arm*

## 5.6. Development work: Cycab

**Participants:** Fabien Spindler, Andrea Cherubini.

The Cycab is a four wheel drive autonomous electric car dedicated to vision-based mobile robotic applications (see Fig. 2.b). A pan-tilt head (Biclops PTM) equipped with a firewire Marlin camera with about 70 degrees field of view is mounted on the front bumper. The Cycab is equipped with two computers connected through an internal network: a PC dedicated to the low level control of the actuators, and a laptop connected to the camera and dedicated to high level visual servoing applications.

At the end of this year, a new and more generic low level controller coming from Inria Grenoble - Rhônes-Alpes was tested with success. New software developments are in progress in order to interface our framework with this new controller.

Our vision-based navigation scheme in outdoor urban environments is under modification to improve the path following precision (see Section 8.2.4), as well as the accuracy in navigation from a visual memory [28].

# 6. New Results

## 6.1. Visual servoing

### *6.1.1. Visual features from a spherical projection model*

**Participants:** Roméo Tatsambon Fomena, François Chaumette.

This study is directly related to the search of adequate visual features, as described in Section 3.1. The approach we developed this year is based on the spherical projection model since it provides interesting geometrical properties. It also allows considering the same modeling for classical perspective cameras and omnidirectional vision sensors such as fish-eye and catadioptric sensors. This year, we have been interested in considering a set of three points as visual features. Decoupling properties have been obtained by using the distances between the points on the sphere, which are invariant to any rotation. The three other features used to control the robot orientation are based on a particular rotation matrix. This particular choice of features allowed to revisit the classical singular configurations exhibited a long time ago, but with a very complex demonstration. Furthermore, simulation results have shown a wide convergence domain even in the presence of points depth estimation errors.

### *6.1.2. Photometric visual servoing*

**Participant:** Éric Marchand.

One of the main problems in visual servoing is to extract and track robustly the image measurements $\mathbf{x}(t)$ that are used to build the visual features $\mathbf{s}(\mathbf{x}(t))$ (see equation (1)) involved in the control scheme. This may lead to complex and time consuming image processing algorithms, and may increase the effect of image noise. To cope with this problem, we proposed to use directly photometric features as input of the control scheme. More precisely, the luminance of all pixels in the image, that is $\mathbf{s}(\mathbf{x}(t)) = \mathbf{I}(t)$, is used as input of the control scheme.

This year, in collaboration with Christophe Collewet who is now a member of the Fluminance team, we proposed a way to perform visual servoing tasks from color attributes. This approach can be seen as an extension of our previous works based on the luminance. Indeed, as we did for the luminance, color attributes are directly used in the control law avoiding therefore any complex images processing as features extraction or matching. We proposed several potential color features and then a way to select a priori the best choice among them with respect to the scene being observed [31].

### *6.1.3. Mutual information-based visual servoing*

**Participants:** Amaury Dame, Éric Marchand.

This work is related to the photometric features modeling (see previous section 6.1.2). The goal remains the same, positioning a robot in a desired position using only one image taken from this position without using features extraction. Visual servoing is achieved by using directly the information of the image. In this study, mutual-information is used as visual feature for visual servoing and involved in a new control law that we have developed to control the 6 dof of a robot. Among various advantages, this approach does not require any matching nor tracking step, it is robust to large illumination variation and allows considering, within the same task, different image modalities [34]. The same work on second order derivatives, as in the tracking problem described in Section 6.4.5, has been performed and allows reaching the desired position with more accuracy and using less parameters, causing a nicer trajectory of the camera in the 3D space. Experiments have been realized on the Afma 6 robot (see Figure 2.a) to demonstrate these advantages.

### 6.1.4. Design of new control schemes

**Participants:** Mohammed Marey, François Chaumette.

This study is devoted to the design of new kinematics control schemes. This year, we have developed a new projection operator for the redundancy framework. Classically, this operator allows considering the components of any secondary task that do not perturb the regulation to zero of the primary task. This means that some degrees of freedom have to remain available, which is very restrictive in practice. The new projection operator does not consider all the components of the main task, but its norm, which involves only one scalar constraint, instead of several, while preserving the stability properties of the system. The new projection operator has been validated using as main task a visual homing that induces all the six degrees of freedom of the system and trajectory following as secondary task. Current works are devoted to consider joints limits avoidance.

### 6.1.5. Visual servoing for aircrafts

**Participants:** Laurent Coutard, Xiang Wang, François Chaumette.

This study aims at developing visual servoing control schemes for fixed wing aircrafts. The first application we considered was the automatic landing in the scope of the European FP6 Pegase project (see Section 8.3.1). After modeling decoupled visual features based on the measurements that can be extracted from the image of the runway (typically, its border and central lines), a simple lateral control scheme has been derived. A longitudinal controller using both 2D and 3D data has also been designed. Both controllers have been integrated in the Pegase simulator and assessed by the industrial partners.

At the end of the year, we have started a new study devoted to the automatic landing on an aircraft carrier.

### 6.1.6. Multi sensor-based control

**Participants:** Olivier Kermorgant, François Chaumette.

This study is realized within the ANR Psirob Scuav project (see Section 8.2.2). We are interested in fusing the data provided by several sensors directly in the control law, instead of estimating the state vector. For that, we have first considered autocalibration methods to estimate the intrinsic and extrinsic parameters of sensors such as cameras and inertial measurement units. The method we have developed is based on the simultaneous measure of the robot velocity and features velocity in the sensor space. It has been validated through experimental results using a classical camera.

### 6.1.7. Visual servoing of non-holonomic mobile robots

**Participants:** Andrea Cherubini, François Chaumette.

This long-term study is devoted to appearance-based navigation from an image database. It is carried out in the scope of the ANR Tosa Cityvip project (see Section 8.2.4). The navigation relies on a monocular camera, and the navigation path is represented as a set of reference images, acquired during a preliminary teaching phase. This year, we have developed a new control scheme that is based on a sliding reference, instead of a set of static references. It allows reaching a good compromise between small 3D tracking errors and memory storage constraints, while providing a smoother behavior, as validated through experiments obtained with the Cycab vehicle [28].

We have also started a study in order to be able to avoid potential obstacles during the navigation. For that, we use a pan-tilt camera so that it is able to observe the environment along the path while avoiding the obstacles. A new control scheme has been developed and validated thanks to simulation results.

### *6.1.8. MEMS micro-assembly*

**Participant:** Éric Marchand.

This work has been done in collaboration with FEMTO-ST/AS2M in Besançon. Robotic microassembly is a promising way to build micro-metric components based on 3D compound products where the materials or the technologies are incompatible: structures, devices, MEMS, MOEMS,... In this work the relevance of real-time 3D visual tracking and servoing has been demonstrated. The poses of the MEMS are supplied in real time by the 3D model-based tracking algorithm we developed few years ago [5]. The assembly of 400 $\mu$m × 400 $\mu$m × 100 $\mu$m parts by their 100 $\mu$m × 100 $\mu$m × 100 $\mu$m notches with a mechanical play of 3 $\mu$m is achieved with a rate of 41 seconds per assembly. Assembly of a complex compound has also been demonstrated [40],[41].

## 6.2. Medical robotics

### *6.2.1. Ultrasound image-based visual servoing*

**Participants:** Rafik Mebarki, Alexandre Krupa, François Chaumette.

We continue our works dedicated to controlling the motion of a 2D ultrasound probe actuated by a medical robot in order to reach and to track a desired cross-section image. The visual servoing techniques available in the literature are devoted to optical systems that differ completely from 2D ultrasound ones in the sense that the latters provide full information in their observation plane but none at all outside. Furthermore, the variation of the ultrasound cross-section image due to the probe out-of-plane motion strongly depends on the 3D shape of the observed object with which the 2D ultrasound probe is interacting.

This year, we proposed in [38] a new technique affording visual servoing without the knowledge of a 3D model of the soft tissue of interest. In that work, we made use of the image moments of the cross-section as visual features by deriving the analytical form of the interaction matrix relating their variation to the probe motion. To afford model-free control, the object surface normal vector is estimated on line. We obtained satisfactory results in simulations, experiments on an ultrasound phantom, and *ex-vivo* experiments on a motionless kidney immersed in a water-filled tank.

### *6.2.2. 3D robot registration from ultrasound images*

**Participants:** Caroline Nadeau, Alexandre Krupa.

We have studied a new approach for rigid registration of a per-operative 2D ultrasound image and a pre-operative 3D image. A visual servoing strategy is used to perform the matching of both image coordinate systems. In this case, the desired image is provided by the ultrasound probe used in the operating room and the current one is obtained by the intersection of a virtual probe with the pre-operative volume. Visual servoing enables then to move this virtual probe to minimize the error of features extracted from both images. To reduce the presence of local minima during the algorithm convergence, a virtual bi-plane probe providing two slides is considered. Preliminary simulation results, obtained by considering non-deformable soft tissue structures, demonstrate the feasibility of this approach.

### *6.2.3. Autonomous control modes for ultrasound probe guidance*

**Participants:** Tao Li, Alexandre Krupa.

This study is realized within the ANR Contint Prosit project (see Section 8.2.6). It consists in developing several autonomous control modes based on ultrasound visual servoing that will assist the physician during a robotized and teleoperated ultrasound examination (tele-echography). The objective of the first autonomous control mode we will develop is to guarantee the visibility of an anatomical element of interest while the physician is teleoperating the robotized probe.

## 6.3. Active vision

### *6.3.1. Find and Focus: Multi Camera Cooperation for Grasping*

**Participants:** Claire Dune, Éric Marchand.

This study was devoted to object grasping using a manipulator within a multi-camera visual servoing scheme. The goal of this project, realized in cooperation with CEA-List (see Section 7.2), was to allow disabled persons to grasp an object with the help of a robot arm mounted either on their wheelchair or on a mobile platform.

First, a method, based on visual servoing and on the epipolar geometry of a multi-view system has been proposed to automatically find and focus the object of interest. We have then dealt with the accurate localization of the object and its rough shape estimation. Considering an active vision process, the motion of the camera is automatically controlled to optimize the estimation of the object structure modeled by a quadric. A method to position the gripper while taking the object shape and pose into account has then been developed. Experiments have been conducted onto the RX90 Staubli robot arm available at CEA-List [15].

## 6.4. Visual tracking

### *6.4.1. Localization for augmented reality*

**Participants:** Fabien Servant, Jean Laneurit, Éric Marchand.

This study focuses on real-time augmented reality for mobile devices. It is related to the France Telecom contract presented in Section 7.1. The goal of this project is to enable augmented reality on mobile devices like GSM or PDA used by pedestrians in urban environments. With a camera and other external sensors, the absolute pose of the camera has to be computed in real-time to show to the end-user geolocalized information in an explicit way.

We have proposed a method for camera pose tracking that uses a partial knowledge on the scene. The method is based on a monocular vision localization method that uses previously known information about the environment (that is, the map of walls) and takes advantages from the various available databases and blueprints to constrain the problem. We have extended this approach in order to consider both a camera and an inertial sensor (IMU)[16].

Other approaches, based on the definition of a differential tracker, have been applied in a museum environment (within the ANR Gamme project, see Section 8.2.3). Automatic recognition techniques adapted to such environments have thus been also developed to bootstrap the algorithm. A Kalman filter over SE(3) has also been developed in order to provide a better tracking and the capability to merge vision information with IMU information.

### *6.4.2. Robust model-based tracking for aircraft localization*

**Participants:** Xiang Wang, Éric Marchand.

This work was realized within the European FP6 Pegase project (see Section 8.3.1). Our goal was to adapt the 3D model-based tracking algorithm Markerless [5] in order to allow localizing an aircraft. For that, we have considered a vectorial database of the surrounding of an airport, provided by Dassault Aviation. The method has been integrated in the Pegase simulation framework for a landing scenario on the Marignane airport starting more than 70 km from the airport. This year we also considered this approach on real aerial infrared images provided by Thales Optronic.

### *6.4.3. Robust tracking for controlling small helicopters*

**Participants:** Céline Teulière, Éric Marchand.

The motivation of this work is to develop tracking algorithms that are suitable for the control of small UAV (X4 flyers). In the work carried out this year, the model-based tracking problem has been considered. Assuming a 3D model of the edges of an object is known, the tracking then consists in finding the camera pose which best aligns the projection of this model with the edges of the image.

The existing deterministic approaches (virtual visual servoing, Newton's minimization,...) usually suffer from possible ambiguities when tracking edges, since different edges may show very similar appearances leading to tracking errors. In order to handle these ambiguities, an optimisation method has been designed in which several hypotheses are maintained at the edge-tracking level, to retrieve several possible camera poses. This process is then used to optimize the best particles of a particle filter. Particle filtering framework allows the tracking to be robust to occlusions and large displacements that are expected in the considered application.

Tracking experiments have been conducted using image sequences from the embedded camera of the X4 flyer developed by CEA-List, and will soon be tested online. Current work aims at fusing inertial data from the UAV with the visual tracking, to improve the prediction of the filter and build an estimate of the UAV's velocity.

#### 6.4.4. *Omnidirectional stereovision*

**Participant:** Éric Marchand.

This study is a joint work with Guillaume Caron and El Mustapha Mouaddib from MIS lab at the Université Jules Verne in Amiens. The motivation of this work is to take advantage of both the wide field of view induced by catadioptric cameras and of the redundancy brought by stereovision. Merging these two characteristics in a single sensor is obtained by combining a single camera and multiple mirrors. Within this framework we proposed a method to calibrate the stereo-catadioptric sensor. We also proposed a 3D model-tracking algorithm that allows a robust tracking of 3D objects using stereo catadioptric images given by this sensor. This work relies on an adapted virtual visual servoing approach, a non-linear pose computation technique. The model takes into account central projection and multiple mirrors. Results show robustness in illumination changes, mistracking and even higher robustness with four mirrors than with two [27].

#### 6.4.5. *Objects tracking from mutual information*

**Participants:** Amaury Dame, Éric Marchand.

This study originally focuses on rigid object tracking in non-structured environments. One of the main problem of tracking in outdoor environment is to deal with occlusions and illumination variations. The method used is based on a differential motion estimation. As in Section 6.1.3, to be robust to changes of illuminations and occlusions, our approach is to use information of the image (as defined by Shannon) instead of using directly luminences. A metric derived from information theory, mutual information, is considered.

This metric has first been considered to replace the classical SSD tracker within a KLT-like tracker [35]. Within this context we also proposed a new way to extract interest points that are features to be tracked using this criterion.

Since mutual information is insensitive to changes in the lighting condition and to a wide class of non-linear image transformation, it is widely used in multi-modal image registration and more recently in motion estimation. This work shows that considering second order derivatives of mutual information allows reaching a better convergence frequency and a better accuracy. Experiments on planar object tracking and on 3D localization have been realized that validate this approach with respect to illumination changes and multi-modal images.

# 7. Contracts and Grants with Industry

## 7.1. France Telecom R&D: Cifre convention

**Participants:** Fabien Servant, Éric Marchand.

*no. Inria 2231, duration : 36 months.*

This contract was devoted to support the Cifre convention between France Telecom R&D and Inria regarding Fabien Servant's Ph.D. (see Section 6.4.1). The goal of the Ph.D. was to enable augmented reality on mobile devices like GSM or PDA used by pedestrians in urban environments. More precisely, its aim was to compute the absolute pose of the camera to show to the end-user geolocalized information in an explicit way.

## 7.2. CEA List: Clickrog: Object grasping for disabled persons

**Participants:** Claire Dune, Éric Marchand.

*no. Inria 1457, duration : 36 months.*

This contract finished this year. It was also supported by the Brittany Council ("krog" means grasping in the Breton language) through a grant to Claire Dune for her Ph.D. The goal of this project was to allow disabled persons to grasp an object with the help of a robotic arm mounted on a wheel chair. This task should be achieved with a minimum of a priori information regarding the environment, the considered object, etc. The work ended this year by the Ph.D. defense of Claire Dune [15]. The work that had been realized in this project is described in Section 6.3.1.

# 8. Other Grants and Activities

## 8.1. Regional initiatives

### 8.1.1. Brittany Council: Clickrog: Object grasping for disabled persons

**Participants:** Claire Dune, Éric Marchand.

*no. Inria 1286, duration : 36 months.*

This project was also supported by the CEA/List and is described in Section 7.2.

## 8.2. National initiatives

### 8.2.1. PEA Tarot

**Participants:** Fabien Spindler, François Chaumette.

*duration: 30 months.*

This project was a large project realized for the DGA through a consortium led by Thales Optronics. It ended in July 2009. We worked in close collaboration with the ARobAS team at Inria Sophia Antipolis-Méditerranée, sharing an engineer, Melaine Gautier, who participated to software developments. This project was about the development of visual tracking algorithms and about the vision-based control of non-holonomic vehicles. Within this project, our work consisted in developing 2D image-based tracking algorithms in complex outdoor scenes. The algorithms provided previously using points of interest have been improved. New functionalities have been added and our contribution was ported to the DGA's autonomous military terrestrial vehicle dedicated to survey missions.

### 8.2.2. ANR Psirob Scuav project

**Participants:** Olivier Kermorgant, François Chaumette.

*no. Inria 2435, duration: 42 months.*

This project, led by Tarek Hamel from I3S, started in June 2007. It is realized in collaboration with I3S, the EPI ARobAS at Inria Sophia Antipolis-Méditerranée, Heudiasyc in Compiègne, the CEA-List and the Bertin company. It is devoted to the sensor-based control of small helicopters for various applications (stabilization landing, target tracking, etc.). The corresponding scientific work is described in Section 6.1.6.

### 8.2.3. ANR AM Gamme project

**Participants:** Jean Laneurit, Éric Marchand.

*no. Inria 2861, duration: 36 months.*

This project started in March 2008. It is realized in collaboration with Orange Labs, CEA Leti, Movea, Polymorph, and the Museum of fine arts in Rennes.

The Augmented Reality (AR) concept aims to enhance our real world perception, combining it with fictitious elements. AR research is concerned with the different methods used to augment live video imagery with coherent computer generated graphics. The combination of mobile technologies and AR will allow the design of a video rendering system with an augmentation of the real world depending on user localisation and orientation.

This project is focused on indoor environments with the implementation of AR technologies on mobile devices as main objective. The experimental field proposed is the Museum, a controlled environment (constant lightening and location of objects) without some of the perturbations of outdoor environments. We do estimate that a successful museum prototype could be used as the backbone of many other indoor and outdoor AR applications.

Within this project we are involved in tracking and sensor fusion parts of the AR process.

### 8.2.4. ANR Tosa CityVIP project

**Participants:** Andrea Cherubini, Éric Marchand, François Chaumette.

*no. Inria 3208, duration: 36 months.*

This project, managed by Lasmea, started in June 2008. It involves eight partners, including Lagadic. The project consists of enhancing the autonomy of urban vehicles by integrating sensor-based techniques with a geographical database. Within CityVIP, Lagadic provides its expertise in vision-based localization and vision-based navigation, including safe navigation in the presence of obstacles. The work that we have realized within this project is described in Section 6.1.7.

### 8.2.5. ANR Psirob RobM@rket project

**Participants:** Guillaume Fortier, Éric Marchand.

*no. Inria 3005, duration: 36 months.*

This project started in March 2008. It is realized in collaboration with BA Systèmes, CEA List, and Université de Caen. RobM@rket project aims at developing automated applications for order picking in a fast-expanding business which mainly includes manual tasks. The system would apply to packaging before dispatching items ordered on a website through an online catalogue including more than 1000 references or to order picking with orders dedicated to kitting.

The robotic system is made of a PLC mobile platform of AGV type (Automatic Guided Vehicles, by BA Systèmes) and of an industrial robot arm. This platform is used to integrate several algorithms allowing picking up selected items in a warehouse through a command file and bringing them back for dispatching or assembling them. The items can be either methodically stored or jumbled in the boxes. Our current work consists in developing vision-based objects localization techniques for grasping them.

### 8.2.6. ANR Contint Prosit project

**Participants:** Tao Li, Alexandre Krupa.

*no. Inria 3585, duration: 36 months.*

This project is a multidisciplinary industrial research type project led by the Prisme lab in Bourges. It started in December 2008 in collaboration with Lirmm in Montpellier, LMS in Poitiers, CHU of Tours, and the Robosoft company. The goal of this project is to develop an interactive master-slave robotic platform for medical diagnosis applications (tele-echography) and to develop a cluster of interactive functionalities combining visual servoing, force control, haptic feedback, virtual human interface, and 3D representation of organs. Within this project, we study and develop autonomous control modes that directly make use of visual data extracted from the 2D ultrasound image and force measurement to move the ultrasound probe.

### 8.2.7. ANR Contint USComp project

**Participants:** Alexandre Krupa, François Chaumette.

*no. Inria 3560, duration: 36 months.*

This project, led by Alexandre Krupa, started in December 2008. It involves a collaboration with the Visages team in Rennes, LSIIT in Strasbourg and Lirmm in Montpellier. Its goal is to provide methodological solutions for real-time compensation of soft tissues motion during ultrasound imaging. The approach consists in synchronizing the displacement of a 2D or 3D ultrasound transducer to stabilize the observed image by the use of a robotic arm actuating the ultrasound probe. The problematic concerns more specifically the use in the control scheme of the per-operative ultrasound image, the interaction force between the probe and the soft tissues and the measurements of external signals providing the breathing state of the patient. Our current work consists in developing a software simulator that generates the ultrasound image observed by a virtual probe interacting with a moving and deforming virtual organ.

## 8.3. International co-operation

### *8.3.1. FP6 Pegase*

**Participants:** Xiang Wang, François Chaumette, Éric Marchand.

*no. Inria 1832, duration: 36 months.*

This FP6 project finished this year. It was managed by Dassault Aviation and grouped many industrial and academic partners (Alenia Aeronautica, Eurocopter, EADS, Walphot, I3S, EPFL, ETHZ, IST, JSI). It was concerned with the automatic landing of fixed wing aircrafts and helicopters using a vision sensor. In this project, we were the leader of the workpackage devoted to visual tracking and visual servoing. The scientific work realized in this project is described in Sections 6.1.5 and 6.4.2.

### *8.3.2. Visiting scientists*

- Prof. Ryuta Ozawa from Ritsumeikan University, Japan, has spent a one-year sabbatical in our group from September 2008 till August 2009.
- Guillaume Caron from MIS in Amiens has spent a one-month visit in November 2009.
- Short visit by Vincent Lepetit (EPFL), Olivier Stasse (JRL/AIST Tsukuba), Luis Hernandez Santana (Univ. Marta Abreu de Las Villas, Cuba).

# 9. Dissemination

## 9.1. Leadership within scientific community

- É. Marchand and F. Chaumette are scientific experts for the DGRI (Direction Générale de la Recherche et de l'Innovation) of the French ministry of research.
- F. Chaumette is a member of the evaluation committee of the ANR Psirob projects.
- F. Chaumette is a member of the Scientific Council of the GdR on Robotics.
- F. Chaumette was a member of the selection committee for a Faculty position at the Université de Nice.
- E. Marchand was a member of the selection committee for two Faculty positions at the Université de Rennes 1.
- F. Chaumette is the Head of the CUMIR of the INRIA centre Rennes-Bretagne Atlantique (*Commission des Utilisateurs des Moyens Informatiques*).
- *Editorial boards of journals*
  - F. Chaumette is in the Editorial Board of the Int. Journal of Robotics Research.

- F. Chaumette was in charge with Peter Corke (CSIRO Brisbane) and Paul Newman (Univ. Oxford) of a special issue on robot vision to appear in the Int. Journal of Robotics Research in 2010.
- F. Chaumette is Associate Editor of the Int. Journal of Optomechatronics.

- *Conference organization*
  - É. Marchand and A. Krupa have been co-chairs of the organizing committee of the national conference Orasis'2009 that was held in Tregastel in June 2009 [47].
- *Technical program committees of conferences*
  - F. Chaumette: ICRA'09, CISA'09, JNRR'09, ETFA'09, IROS'09, ISOT'09, Robotica'09, ICRA'10.
  - É. Marchand: JNRR'09, CVPR 2009, ICCV 2009, ACCV 2009, ISMAR'09, CVPR'10.
- *Ph.D. and HdR jury*
  - F. Chaumette: Damien Martin-Guillerez (Ph.D., Irisa, Rennes), Youcef Mezouar (HdR, Lasmea, Clermont-Ferrand, reviewer),
  - É. Marchand: Wai Ho Li, (Ph.D., Monash University, Melbourne, Australia, reviewer), Chadi Albitar (Ph.D., LSIIT, Strasbourg, reviewer), Brahim Tamadazte (Ph.D., Femto, Besançon), Raphaël Lerbour (Ph.D., Université de Rennes 1, president)

## 9.2. Teaching

- Master M2RI of Computer Science, Ifsic, Université de Rennes 1 (É. Marchand): 3D computer vision, augmented reality.
- Master SIBM (Signals and Images in Biology and Medicine), Université de Rennes 1, Brest and Angers (A. Krupa): medical robotics for physician students.
- Master M2R at Université Picardie Jules Vernes in Amiens (F. Chaumette): visual servoing
- ESIR, Université de Rennes 1 (E. Marchand: 3D vision, image recognition, color images, programming tools for image processing; F. Chaumette: visual servoing).
- Undergraduate student interns: Maharavo Andriamiarisoa (Master ENSPS Strasbourg), Tao Li (INSA, Rennes), Emilio Roth (UNAM, Mexico).

## 9.3. Participation in seminars, invitations, awards

- A. Krupa gave a plenary talk at JNRR'09 [26].
- F. Chaumette gave a plenary talk at the international conference COGIS 2009 [25].

# 10. Bibliography

## Major publications by the team in recent years

[1] F. Chaumette. *Image moments: a general and useful set of features for visual servoing*, in "IEEE Trans. on Robotics and Automation", vol. 20, n$^{o}$ 4, August 2004, p. 713-723, http://www.irisa.fr/lagadic/pdf/2004_itro_chaumette.pdf.

[2] F. Chaumette. *Potential problems of stability and convergence in image-based and position-based visual servoing*, in "The Confluence of Vision and Control", LNCIS Series, No 237, Springer-Verlag, 1998, p. 66-78, http://www.irisa.fr/lagadic/pdf/1998_lncis_chaumette.pdf.

[3] F. CHAUMETTE, S. HUTCHINSON. *Visual servo control, Part I: Basic approaches*, in "IEEE Robotics and Automation Magazine", vol. 13, n$^{o}$ 4, December 2006, p. 82-90, http://www.irisa.fr/lagadic/pdf/2006_ieee_ram_chaumette.pdf.

[4] F. CHAUMETTE, S. HUTCHINSON. *Visual servo control, Part II: Advanced approaches*, in "IEEE Robotics and Automation Magazine", vol. 14, n$^{o}$ 1, March 2007, p. 109-118, http://www.irisa.fr/lagadic/pdf/2007_ieee_ram_chaumette.pdf.

[5] A. COMPORT, E. MARCHAND, M. PRESSIGOUT, F. CHAUMETTE. *Real-time markerless tracking for augmented reality: the virtual visual servoing framework*, in "IEEE Trans. on Visualization and Computer Graphics", vol. 12, n$^{o}$ 4, July 2006, p. 615–628, http://www.irisa.fr/lagadic/pdf/2006_ieee_tvcg_comport.pdf.

[6] A. CRÉTUAL, F. CHAUMETTE. *Visual servoing based on image motion*, in "Int. Journal of Robotics Research", vol. 20, n$^{o}$ 11, November 2001, p. 857–877, http://www.irisa.fr/lagadic/pdf/2001_ijrr_cretual-1.pdf.

[7] B. ESPIAU, F. CHAUMETTE, P. RIVES. *A new approach to visual servoing in robotics*, in "IEEE Trans. on Robotics and Automation", vol. 8, n$^{o}$ 6, June 1992, p. 313-326, http://www.irisa.fr/lagadic/pdf/1992_itra_espiau.pdf.

[8] A. KRUPA, F. CHAUMETTE. *Guidance of an Ultrasound Probe by Visual Servoing*, in "Advanced Robotics, Special issue on "Selected papers from IROS'05"", vol. 20, n$^{o}$ 11, November 2006, p. 1203–1218, http://www.irisa.fr/lagadic/pdf/2006_ar_krupa.pdf.

[9] E. MALIS, F. CHAUMETTE, S. BOUDET. *2 1/2 D visual servoing*, in "IEEE Trans. on Robotics and Automation", vol. 15, n$^{o}$ 2, April 1999, p. 238-250, http://www.irisa.fr/lagadic/pdf/1999_ieeera_malis.pdf.

[10] N. MANSARD, F. CHAUMETTE. *Task sequencing for sensor-based control*, in "IEEE Trans. on Robotics", vol. 23, n$^{o}$ 1, February 2007, p. 60-72, http://www.irisa.fr/lagadic/pdf/2007_itro_mansard.pdf.

[11] E. MARCHAND, N. COURTY. *Controlling a camera in a virtual environment*, in "The Visual Computer Journal", vol. 18, n$^{o}$ 1, February 2002, p. 1-19, http://www.irisa.fr/lagadic/pdf/2002_vc_marchand.pdf.

[12] E. MARCHAND, F. SPINDLER, F. CHAUMETTE. *ViSP for visual servoing: a generic software platform with a wide class of robot control skills*, in "IEEE Robotics and Automation Magazine", vol. 12, n$^{o}$ 4, December 2005, p. 40-52, http://www.irisa.fr/lagadic/pdf/2005_ieee_ram_marchand.pdf.

[13] Y. MEZOUAR, F. CHAUMETTE. *Path planning for robust image-based control*, in "IEEE Trans. on Robotics and Automation", vol. 18, n$^{o}$ 4, August 2002, p. 534-549, http://www.irisa.fr/lagadic/pdf/2002_icra_mezouar.pdf.

[14] M. PRESSIGOUT, E. MARCHAND. *Real-Time Hybrid Tracking using Edge and Texture Information*, in "Int. Journal of Robotics Research, IJRR", vol. 26, n$^{o}$ 7, July 2007, p. 689-713, http://www.irisa.fr/lagadic/pdf/2007_ijrr_pressigout.pdf, special joint issue IJCV/IJRR on robot and vision.

# Year Publications

## Doctoral Dissertations and Habilitation Theses

[15] C. DUNE. *Localisation et caractérisation d'objets inconnus à partir d'informations visuelles : vers une saisie intuitive pour les personnes en situation de handicap*, Université de Rennes 1, Mention informatique, April 2009, http://www.irisa.fr/lagadic/pdf/2009_these_dune.pdf, Ph. D. Thesis.

[16] F. SERVANT. *Localisation et cartographie simultanées en vision monoculaire et en temps réel basé sur les structures planes*, Université de Rennes 1, Mention informatique, June 2009, http://www.irisa.fr/lagadic/pdf/2009_these_servant.pdf, Ph. D. Thesis.

### Articles in International Peer-Reviewed Journal

[17] O. BOURQUARDEZ, R. MAHONY, N. GUENARD, F. CHAUMETTE, T. HAMEL, L. ECK. *Image-based visual servo control of the translation kinematics of a quadrotor aerial vehicle*, in "IEEE Trans. on Robotics", vol. 25, n$^{o}$ 3, June 2009, p. 743-749, http://www.irisa.fr/lagadic/pdf/2009_TRO_bourquardez.pdfau.

[18] F. DIONNET, E. MARCHAND. *Stereo tracking and servoing for space applications*, in "Advanced Robotics", vol. 23, n$^{o}$ 5, April 2009, p. 579-599, http://www.irisa.fr/lagadic/pdf/2009_ar_dionnet.pdf.

[19] A. KRUPA, G. FICHTINGER, G. HAGER. *Real-time motion stabilization with B-mode ultrasound using image speckle information and visual servoing*, in "The International Journal of Robotics Research, IJRR", vol. 28, n$^{o}$ 10, 2009, p. 1334-1354, http://www.irisa.fr/lagadic/pdf/2009_ijrr_krupa.pdf, Special Issue on Medical Robotics, Ayache, N. and Desai, J. (Eds.) us ca .

[20] N. MANSARD, F. CHAUMETTE. *Directional redundancy for robot control*, in "IEEE Trans. on Automatic Control", vol. 54, n$^{o}$ 6, June 2009, p. 1179-1192, http://www.irisa.fr/lagadic/pdf/2009_TAC_mansard.pdf.

[21] N. MANSARD, A. REMAZEILLES, F. CHAUMETTE. *Continuity of varying-feature-set control laws*, in "IEEE Trans. on Automatic Control", vol. 54, n$^{o}$ 11, November 2009, p. 2493-2505, http://www.irisa.fr/lagadic/pdf/2009_TAC2_mansard.pdf.

[22] S. SEGVIC, A. REMAZEILLES, A. DIOSI, F. CHAUMETTE. *A mapping and localization framework for scalable appearance-based navigation*, in "Computer Vision and Image Understanding", vol. 113, n$^{o}$ 2, February 2009, p. 172-187, http://www.irisa.fr/lagadic/pdf/2009_cviu_segvic1.pdf.

[23] R. TATSAMBON FOMENA, F. CHAUMETTE. *Improvements on visual servoing from spherical targets using a spherical projection model*, in "IEEE Trans. on Robotics", vol. 25, n$^{o}$ 4, August 2009, p. 874-886, http://www.irisa.fr/lagadic/pdf/2009_TRO_tatsambon.pdf.

### Articles in National Peer-Reviewed Journal

[24] E. MARCHAND, M. PRESSIGOUT. *Un panorama des techniques de suivi visuel temps-réel pour la réalité augmentée*, in "Technique et Science Informatiques, TSI", vol. 28, n$^{o}$ 6-7, 2009, p. 921-943, http://www.irisa.fr/lagadic/pdf/2009_TSI_marchand.pdf, Numéro spécial "Innovations en réalités virtuelle et augmentée".

### Invited Conferences

[25] F. CHAUMETTE. *Recent advances in visual servoing*, in "Cognitive Systems with Interactive Sensors, COGIS'09, (Plenary talk), Paris, France", November 2009.

[26] A. KRUPA. *Asservissement visuel par imagerie médicale*, in "Journées Nationales de la Recherche en Robotique, JNRR'09, Neuvy-sur-Barangeon, France", November 2009, http://www.irisa.fr/lagadic/pdf/2009_jnrr_krupa.pdf.

### International Peer-Reviewed Conference/Proceedings

[27] G. CARON, E. MARCHAND, E. MOUADDIB. *Model Based Pose Estimation For Omnidirectional Stereovision*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 5228-5233, http://www.irisa.fr/lagadic/pdf/2009_iros_caron.pdf.

[28] A. CHERUBINI, F. CHAUMETTE. *Visual navigation with a time-independent varying reference*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 5968-5973, http://www.irisa.fr/lagadic/pdf/2009_iros_cherubini.pdf.

[29] A. CHERUBINI, M. COLAFRANCESCO, G. ORIOLO, L. FREDA, F. CHAUMETTE. *Comparing appearance-based controllers for nonholonomic navigation from a visual memory*, in "ICRA 2009 Workshop on safe navigation in open and dynamic environments: application to autonomous vehicles, Kobe, Japan", May 2009, http://www.irisa.fr/lagadic/pdf/2009_icrawk_cherubini.pdf it .

[30] C. COLLEWET. *Polar snakes: A fast and robust parametric active contour model*, in "IEEE Int. Conf. on Image Processing, ICIP'09, Cairo, Egypt", November 2009, http://www.irisa.fr/lagadic/pdf/2009_icip_collewet.pdf.

[31] C. COLLEWET, E. MARCHAND. *Colorimetry-based visual servoing*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 5438-5443, http://www.irisa.fr/lagadic/pdf/2009_iros_collewet.pdf.

[32] C. COLLEWET, E. MARCHAND. *Photometry-based visual servoing using light reflexion models.*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 701-706, http://www.irisa.fr/lagadic/pdf/2009_icra_collewet.pdf.

[33] P. CORKE, F. SPINDLER, F. CHAUMETTE. *Combining Cartesian and cylindrical coordinates in IBVS*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 5962-5967, http://www.irisa.fr/lagadic/pdf/2009_iros_corke.pdf au .

[34] A. DAME, E. MARCHAND. *Entropy-based visual servoing*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 707-713, http://www.irisa.fr/lagadic/pdf/2009_icra_dame.pdf.

[35] A. DAME, E. MARCHAND. *Optimal Detection and Tracking of Feature Points using Mutual Information*, in "IEEE Int. Conf. on Image Processing, ICIP'09, Cairo, Egypt", November 2009, http://www.irisa.fr/lagadic/pdf/2009_icip_dame.pdf.

[36] A. KRUPA, G. FICHTINGER, G. HAGER. *Rigid motion compensation with a robotized 2D ultrasound probe using speckle information and visual servoing*, in "Advanced Sensing and Sensor Integration in Medical Robotics, Workshop at the IEEE Int. Conf. on Robotics and Automation, Kobe, Japan", D. BURSCHKA, G. HAGER, R. KONIETSCHKE, A. OKAMURA (editors), May 2009, http://www.irisa.fr/lagadic/pdf/2009_icra_workshop_krupa.pdf us ca .

[37] M. MAREY, F. CHAUMETTE. *A temptative to reach a visual singular configuration using Halley's method*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 1122-1127, http://www.irisa.fr/lagadic/pdf/2009_icra_marey.pdf.

[38] R. MEBARKI, A. KRUPA, F. CHAUMETTE. *Modeling and 3D local estimation for in-plane and out-of-plane motion guidance by 2D ultrasound-based visual servoing*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 319-325, http://www.irisa.fr/lagadic/pdf/2009_icra_mebarki.pdf.

[39] O. TAHRI, Y. MEZOUAR, F. CHAUMETTE, P. CORKE. *Generic decoupled image-based visual servoing for cameras obeying the unified projection model*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 1116-1121, http://www.irisa.fr/lagadic/pdf/2009_icra_tahri.pdf pt .

[40] B. TAMADAZTE, T. ARNOULD, S. DEMBÉLÉ, N. LEFORT-PIAT, E. MARCHAND. *Real-time vision-based microassembly of 3D MEMS*, in "IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, AIM 2009, Singapore", July 2009, http://www.irisa.fr/lagadic/pdf/2009_aim_tamadazte.pdf.

[41] B. TAMADAZTE, N. LEFORT-PIAT, E. MARCHAND, S. DEMBÉLÉ. *Microassembly of Complex and Solid 3D MEMS by 3D Vision-based Control*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 3284-3289, http://www.irisa.fr/lagadic/pdf/2009_iros_tamadazte.pdf.

[42] R. TATSAMBON FOMENA, H. YOON, A. CHERUBINI, F. CHAUMETTE, S. HUTCHINSON. *Coarsely Calibrated Visual Servoing of a Mobile Robot using a Catadioptric Vision System*, in "IEEE Int. Conf. on Intelligent Robots and Systems, IROS'09, St Louis, USA", October 2009, p. 5432-5437, http://www.irisa.fr/lagadic/pdf/2009_iros_tatsambon.pdf us .

[43] C. TEULIÈRE, E. MARCHAND, L. ECK. *A combination of particle filtering and deterministic approaches for multiple kernel tracking.*, in "IEEE Int. Conf. on Robotics and Automation, ICRA'09, Kobe, Japan", May 2009, p. 3948-3954, http://www.irisa.fr/lagadic/pdf/2009_icra_teuliere.pdf.

### National Peer-Reviewed Conference/Proceedings

[44] C. NADEAU, C. DUNE. *Vers une saisie en un clic : caractérisation d'un objet 3D à partir d'une reconstruction voxellique*, in "Congrès de jeunes chercheurs en vision par ordinateur, ORASIS'09, Trégastel, France", E. MARCHAND, L. MORIN, A. KRUPA (editors), May 2009, http://www.irisa.fr/lagadic/pdf/2009_orasis_nadeau.pdf.

[45] C. TEULIÈRE. *Approche multi-noyaux pour le suivi temps-réel d'objet mobile*, in "Congrès de jeunes chercheurs en vision par ordinateur, ORASIS'09, Trégastel, France", E. MARCHAND, L. MORIN, A. KRUPA (editors), May 2009, http://www.irisa.fr/lagadic/pdf/2009_orasis_teuliere.pdf.

[46] H. TRAN, E. MARCHAND. *Mot phuong phap doi sanh anh thoi gian thuc*, in "12th national conference on Information Technology and Telecommunication., Hanoï, Vietnam", August 2009, http://www.irisa.fr/lagadic/pdf/2009_tran.pdf, en vietnamien.

### Books or Proceedings Editing

[47] E. MARCHAND, L. MORIN, A. KRUPA (editors). *Actes des 12e Journées ORASIS, Congrès des jeunes chercheurs en vision par ordinateur*, Inria, Trégastel, France, June 2009.