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 COG

Activity Report

2008

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2. Overall Objectives

2.1. Introduction

Keywords: *active vision*, *augmented reality*, *computer vision*, *image sequence*, *robot vision*, *tracking*, *visual servoing*.

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.

2.2. Highlights of the year

2.2.1. Medical robotics

Our works related to visual servoing based on ultrasound image moments (see Section 6.2.1) have been strongly appreciated by both the robotics and medical international communities. A first work has been selected as one of the five finalists for the Best Vision Paper Award at ICRA'2008 [36] and a second work has been retained as one of the three finalists for the Young Scientist Award in Robotics and Interventions at MICCAI'2008 [37].

2.2.2. Visual servoing from non geometrical visual features

Generally, visual servoing control schemes are based on geometrical features such as for instance image points, image moments, or 3D pose. Only few exceptions exist where non geometrical visual features are used as inputs of the control schemes. A long time ago, we had considered parameters characterizing the optical flow [6]. This year, we obtained new original and promising results on photometric visual features (see Section 6.1.2, [30], [31]) and mutual information (see Section 6.1.3).

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 λ 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 Graal 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

Keywords: *augmented reality*, *medical robotics*, *robotics*, *vehicle navigation*.

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 thecontrol 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, Anthony Saunier, 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].

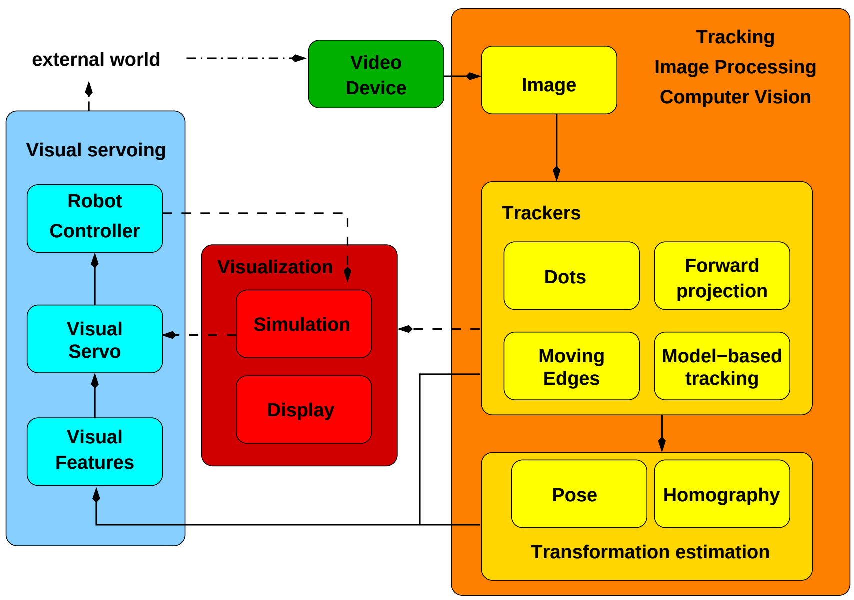


Figure 1. ViSP software architecture.

This year, we continue to improve the software and documentation quality. A new open source version was released in March. It is available at http://www.irisa.fr/lagadic/visp/visp.html. A user guide is also under preparation. 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 hand-eye calibration, and camera calibration tools.

ViSP open source code has been downloaded more than 1000 times in 2008. It is used in research labs in France, USA, Japan, Korea, India, China, Lebanon, Italy, Spain, Portugal, and Hungary. For instance, it is used as a support in a graduate course delivered at MIT.

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.

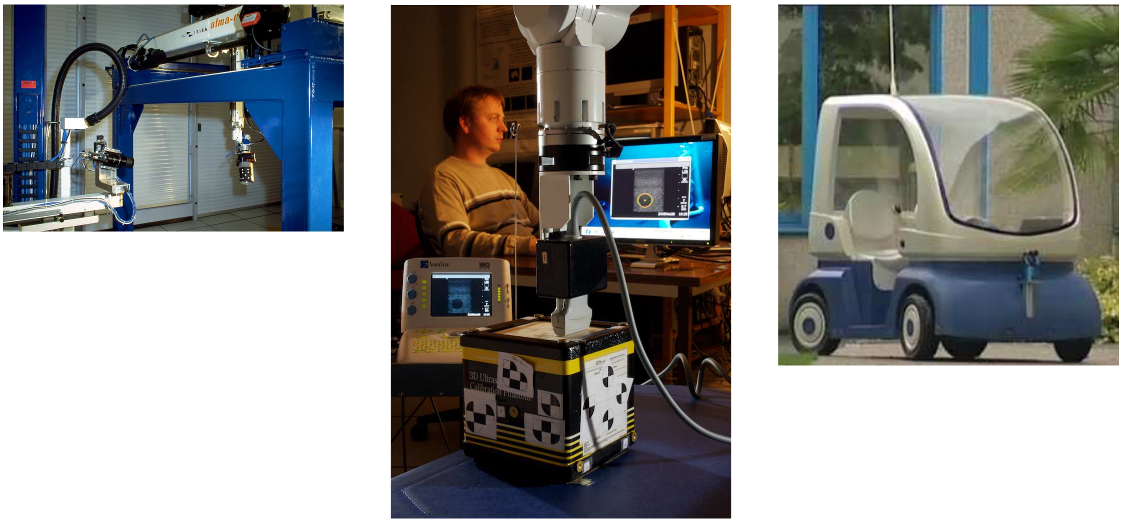
5.4. Development work: Robot vision platforms

Participant: Fabien Spindler.

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 summer, a major upgrade was performed on the Gantry robot. The old VME controller was replaced by an ADEPT controller. We have also changed all the motors and coders by new ones to ensure the durability of this robot. Furthermore, to ensure the security of the users, immaterial barriers were installed. The low level software was then modified to introduce a Cartesian servo of the robot and it was interfaced with ViSP (see Section 5.1). The high level control of the robot is performed on a new PC under Linux which communicates now by firewire with the low-level controller. Most of the existing demonstrations were upgraded to this new material. The same operation has been done in November on the cylindrical robot.

This platform is by far the most-used one by Lagadic members (10 papers published in 2008 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.



(a) (b) (c)

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

5.5. Development work: Medical robot

Participants: Fabien Spindler, Alexandre Krupa.

To validate our researches in medical robotics, we exploit since 2004 a six degrees of freedom medical arm designed by the Sinters company (see Fig. 2.b). 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 via a LAN network the low level controller under QNX. This material is shared betweeen the Lagadic and Visages teams.

At the beginning of the year, electronic problems occur more and more often and lead to a useless system. Since the Sinters company stopped all its activities in robotics, no maintenance could be provided. We spent a lot of time to diagnose the hardware failure, to find its origin and finally to settle the matter. Besides, new software developments were done to better synchronize the images with the corresponding robot poses.

As described in Section 6.2, 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.

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.c). A pan-tilt head (Biclops PTM) equipped with a firewire Marlin camera with about 70 degrees field of view is mounted on the front avoid-shock. 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.

Two visual servoing schemes for reaching and following a continuous curve on the ground have been implemented on the Cycab (see Section 6.1.8 and [29], [28]). Moreover, our vision-based navigation scheme in outdoor urban environments from a visual memory [24] is under modification to improve the path following precision (see Section 8.2.4). The Cycab was also used this year by the Dionysos Inria team to validate researches in the field of mobile internet.

6. New Results

6.1. Visual servoing

6.1.1. Visual features from a spherical projection model

Participants: Roméo Tatsambon Fomena, François Chaumette.

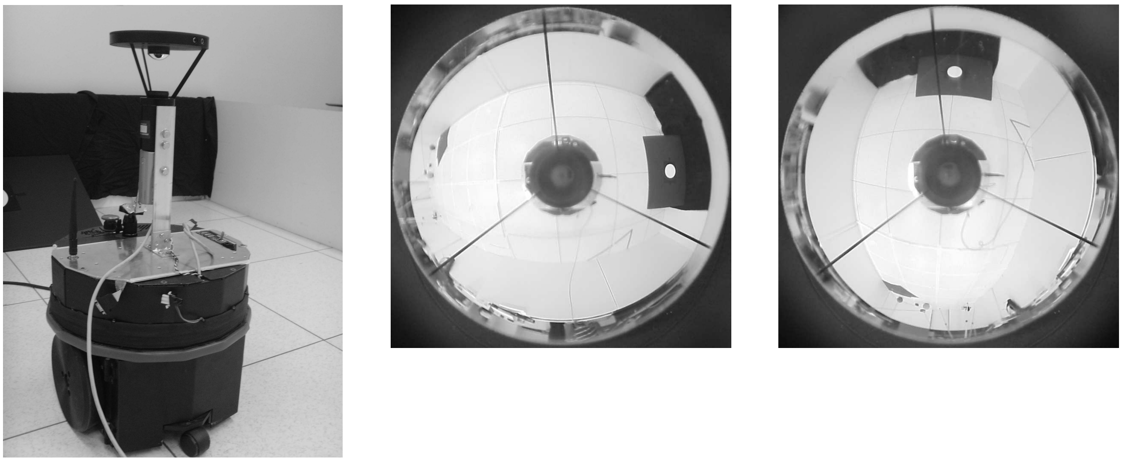
This study is directly related to the search of adequate visual features, as described in Section 3.1. The approach we developed is based on the spherical projection model since it provides interesting geometrical properties. It also allows considering the same modeling for classical perspective cameras and omnidirectional vision sensors such as fish-eye and catadioptric sensors. The classical geometrical features such as points, segments, straight lines and spheres have been revisited using this model, and for each of them, a new set of minimal and decoupled visual features has been exhibited. As for a point, it can be represented by its spherical coordinates, which are suitable for catadioptric sensors with a dead angle in their center. The interests of these features have been experimentally validated at the Beckman Institute (see Section 8.3.4) using a catadioptric sensor mounted on a mobile robot (see Fig 3). The control scheme developed has been shown to be robust to both robot and camera calibration errors, as well as to point depth estimation error. The control scheme obtained for a set of points is similar. The decoupling property has been obtained by using distances 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. Simulation results have shown a wide convergence domain even in the presence of points depth estimation errors.

Finally, as for a sphere marked with two points on its surface, the decoupling of the control scheme has been obtained by using the orientation of the current camera frame with respect to the desired camera frame, which is invariant to any translation [43]. The other three features represent the position of the target up to a scale factor. The stability of the new scheme has been analysed regarding errors on the estimation of the radius of the sphere. The robustness of the control scheme with respect to camera modeling has been validated experimentally using a fisheye camera [42] (see Fig. 4).

6.1.2. Photometric visual servoing

Participants: Eric Marchand, Christophe Collewet.

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 [44], [30]. 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. The modeling has first been based on the hypothesis of Lambertian scene. We have shown that the classical control laws fail in this case due to the strong non linearities in the corresponding cost function. Therefore, we have developed a new control law derived from the particular shape of the cost function. It is first based on a gradient approach and then on a Levenberg-Marquardt-like approach.



(a) (b) (c)

Figure 3. Positioning of a mobile robot with respect to a point: a) Beckman Institute super scout mobile robot equipped with a catadioptric vision system, b) initial image, c) final image.

Figure 4. Visual servoing of a special sphere using a fisheye camera: initial image on the left and desired image on the right.

Experimental results have validated this control law in the case of positioning tasks. The positioning error is always very low. Supplementary advantages are that this approach is few sensitive to partial occlusions and to coarse approximations of the depths required to compute the interaction matrix.

Recently, the interaction matrix has been derived in the more general case of a non Lambertian scene using the Phong or Blinn-Phong illumination model [31], [50]. The method derived is thus able to cope with complex illumination changes due to a dynamic scene (with a moving lighting and/or a moving object) and to specularities occurrence. Experimental results on positioning tasks with respect to non Lambertian objects [50] as well as on target tracking [31] have validated this approach (see Fig. 5 where the object to track was moved by hand).

However, this approach does not model the illumination changes caused by the intensity of the lighting source itself. Therefore, we have investigated the use of color invariants that are well known to be insensitive to such illumination changes. The interaction matrix has been derived for various color invariants, and simulation results have shown that positioning tasks can be achieved under intensity variations of the lighting source.

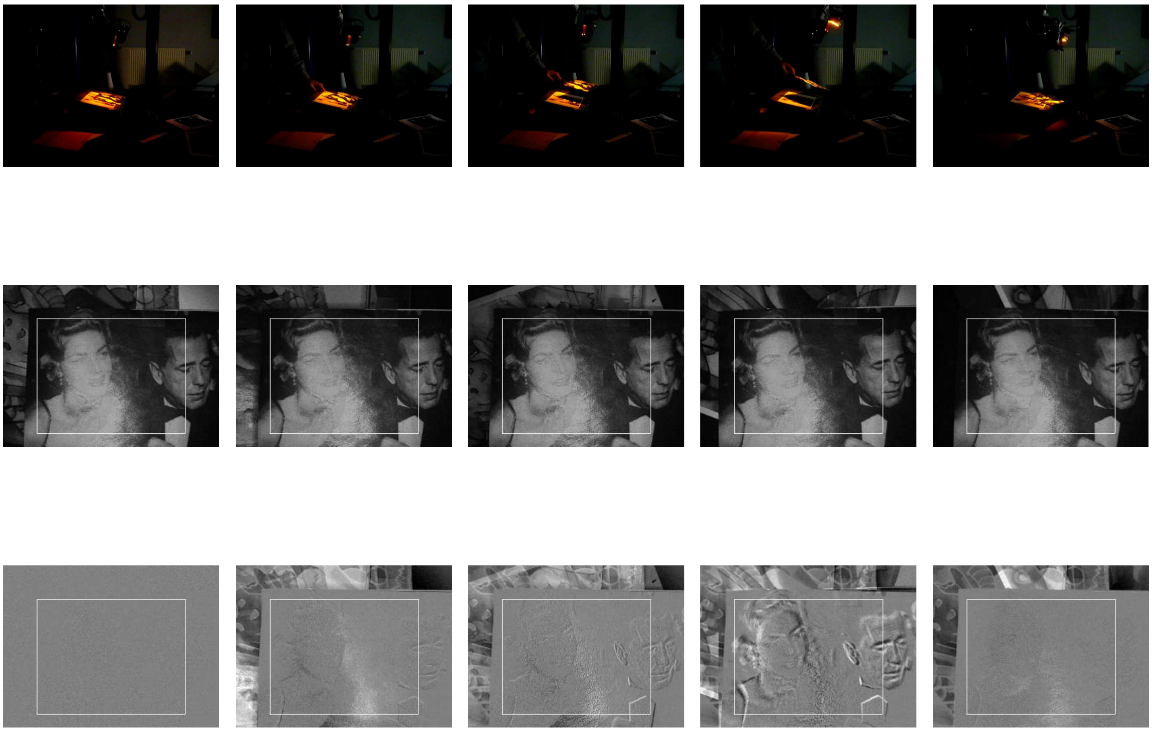


Figure 5. Example of a tracking task considering the complete interaction matrix that integrates specularity, diffuse and ambient terms. External views of the scene at different time (first row), images $\mathbf{I}$ at different time (second row) and corresponding errors $\mathbf{I} - \mathbf{I}^*$ (third row).

6.1.3. Mutual information-based visual servoing

Participants: Amaury Dame, Éric Marchand.

This work is related to the modeling of photometric features. The goal remains the same as in the previous section 6.1.2, that is, positioning a camera to a desired pose using only the current and the desired images, without any geometrical feature extraction. In this study, visual servoing is achieved using the information of the image, in the Shannon sense, as a new visual feature. More precisely, mutual information (which is widely used for registration purpose in medical imaging) allows comparing two images even if a non-linear transformation has been applied to these images. The process is then robust to occlusion and large lighting variations. It also allows considering images acquired using different acquisition modalities. Experiments demonstrating the advantages of this new approach have been realized on the Gantry robot (see Section 2.a and 6).

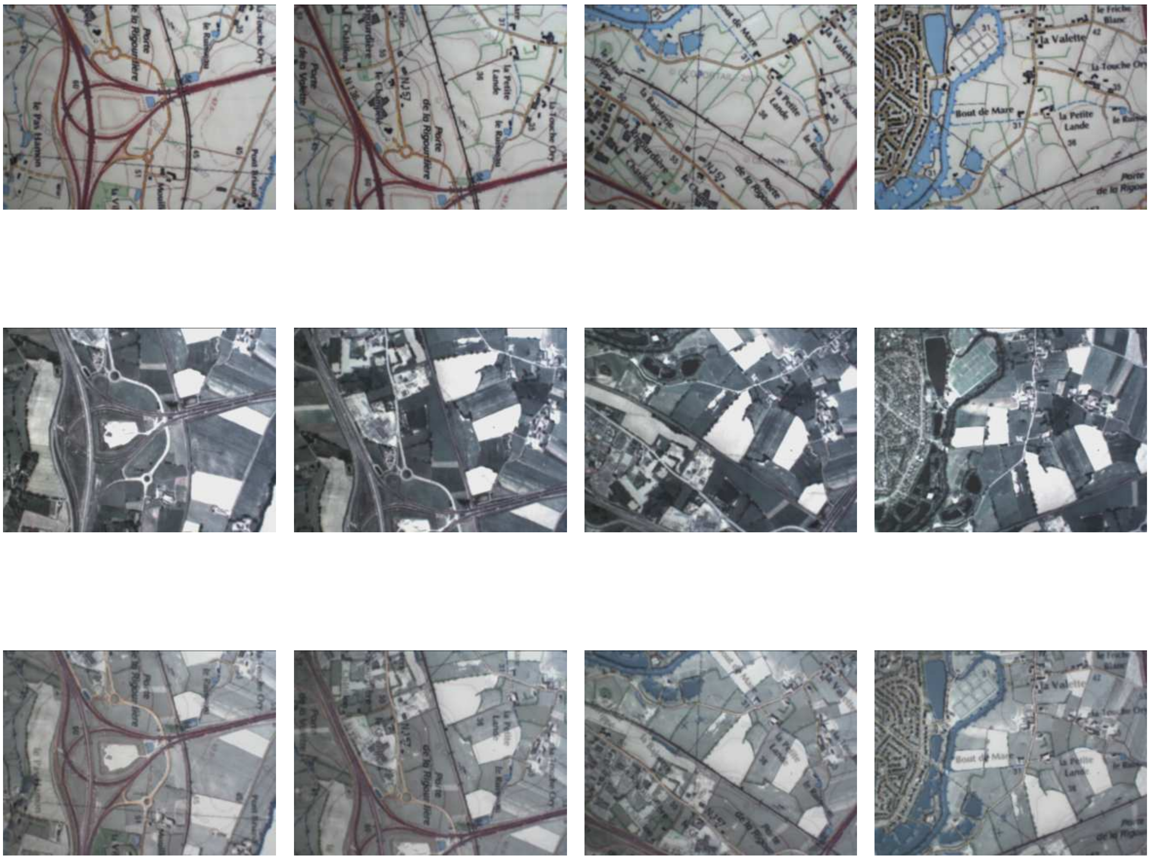


Figure 6. Multi-modal visual servoing based on mutual information in a navigation task. First row: desired images acquired during a learning step; second row: current images acquired during the servo loop; third row: desired images overlaid on the current ones.

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. The first control law that we have developed is based on a linear combination of the interaction matrices computed at the current camera pose and at the desired pose [35]. By selecting the parameter that sets the weight to each matrix, it is possible to adapt the behavior of the control law. We have exhibited some configurations where all the classical control schemes fail in a local minimum while a particular value of the behavior parameter allows the system to converge. Some new singular configurations have also been exhibited for some classical control laws and the new control law allows avoiding them.

We are currently interested in the design of a control scheme that is robust at singular configurations. The goal is to move a camera to a pose where the interaction matrix is singular. It occurs for several configurations when the coordinates of three image points are considered as visual features. It also occurs to move a camera with respect to a circle so that this circle appears centered in the image. The method we are currently developing is based on the Haley's minimization technique that uses the Hessian of the features. For that, we have determined the analytical form of the Hessian matrices for image points coordinates and for the parameters representing an ellipse in the image. Satisfactory simulation results have been obtained but the method has to be improved since our current experimental results are not sufficiently robust to image noise near a singular configuration.

6.1.5. Visual servoing for aircrafts

Participants: Odile Bourquardez, Xiang Wang, François Chaumette.

This study aims at developing visual servoing control schemes for aerial vehicles. As for fixed wing aircrafts, the considered application is the automatic landing in the scope of the European FP6 Pegase project (see Section 8.3.2). 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), we have proposed a visual servoing scheme to align an airplane with respect to the runway. The control scheme has been built by using a linearized model of the airplane dynamics. Then we have applied this control scheme for a complete automatic landing. A desired trajectory which takes into account the airplane dynamics has been designed. Coupling this trajectory and the control law allows the airplane to join its desired path. Then the airplane is controlled to follow the glide path, realize the flare manoeuvre and finally touchdown. Simulation results have been obtained with a quite realistic flight simulator (provided by Dassault Aviation), which is based on a non linear airplane dynamic model. These results have shown that the airplane is able to land automatically by visual servoing [15]. A simpler lateral control scheme has been derived this year and integrated in the Pegase simulator. We are currently working on the control of the zoom of the camera so that the runway appears with a sufficiently large space in the image, which would allow extracting its border lines with higher accuracy.

As for helicopters, we have designed and analysed several control schemes based on the centroid of a target expressed in a spherical coordinate system, for positioning and stabilization tasks. The goal was to find a couple of visual features and control scheme so that the sensitivity to any translational motion was the same. We have experimented the most promising control laws proposed on the X4-flyer developed at CEA-List. It uses a small camera, with wireless video transmission, mounted on the X4-flyer. We have also compared the results with a classical visual servoing scheme using perspective zeroth and first order moments. In practice and as expected, three control schemes have led to demonstrate excellent performances of the system: the perspective image moments control design, as well as two of the control laws using spherical image moments [18].

6.1.6. MEMS micro-assembly

Participant: Eric Marchand.

This work has been done in collaboration with FEMTO-ST 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,... To date, solutions proposed in the literature are based on 2D visual servo because of the lack of accurate and robust 3D measures from the work scene. 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 recently [5]. It is accurate and robust enough to enable a precise regulation toward zero of a 3D error using a classical pose-based visual servo. The assembly of 400μm $\times$ 400μm $\times$ 100μm parts by their 100μm $\times$ 100μm $\times$ 100μm notches with a mechanical play of 3μm is achieved with a rate of 41 seconds per assembly (see Figure 7). The control accuracy reaches 0.3μm in position and $0.2°$ in orientation.

6.1.7. Multi sensor-based control

Participants: David Folio, Olivier Kermorgant, François Chaumette.

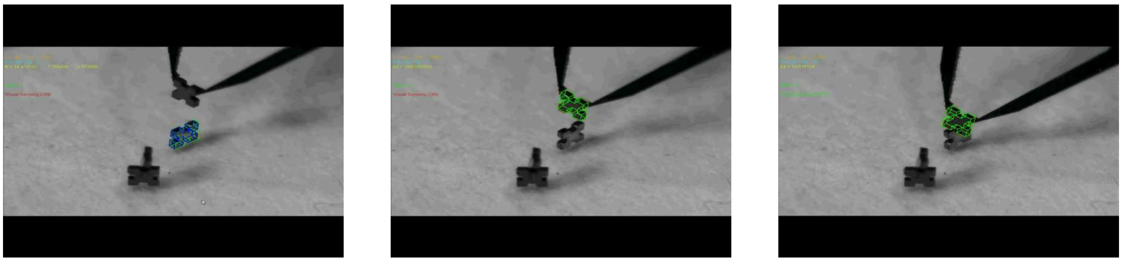


Figure 7. Micro assembly of two 400μm × 400μm × 100μ MEMS using visual servoing.

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 are currently developing autocalibration methods to estimate the intrinsic and extrinsic parameters of sensors such as cameras and inertial measurement unit. The method is based on the simultaneous measure of the robot velocity and features velocity in the sensor space.

6.1.8. Visual servoing of non-holonomic mobile robots

Participants: Andrea Cherubini, François Chaumette.

The two applications that we have studied in the field of vision-based control of non-holonomic mobile robots are path reaching/following, and navigation from an image database.

Firstly, we have developed a visual servoing scheme enabling nonholonomic mobile robots with a fixed pinhole camera to reach and follow a continuous path on the ground. Two versions of the path follower have been implemented: position-based [28] and image-based [29]. For both versions, a Lyapunov-based stability analysis has been carried out, and the performance has been experimentally validated on our CyCab (see Section 5.6). The main contribution of this work is that our scheme requires only a small set of visible path features, along with a coarse camera model, and that it guarantees convergence even when the initial error is large. An experiment using the position-based controller with large initial error is shown in Fig. 8.

The second application we have studied is 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 [24]. This year, we have focused on six selected controllers (one pose-based controller, and five image-based) for replaying the taught path. The controllers have been evaluated and compared in simulations using Webots (available at http://www.cyberbotics.com). We have also considered the possibility of increasing the frequency of the desired reference images; this enables better 3D path tracking but on the other hand requires a larger amount of memory. Current work consists of using a sliding reference in the control scheme to reach a good compromise between 3D tracking and memory storage constraints.

6.2. Medical robotics

6.2.1. Ultrasound image-based visual servoing

Participants: Rafik Mebarki, Alexandre Krupa, François Chaumette.

The objective of this work is to automatically control the motion of a 2D ultrasound probe actuated by a medical robot in order to reach and track a desired cross-section image. The 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 of the 3D shape of the observed object with which the 2D ultrasound probe is interacting.

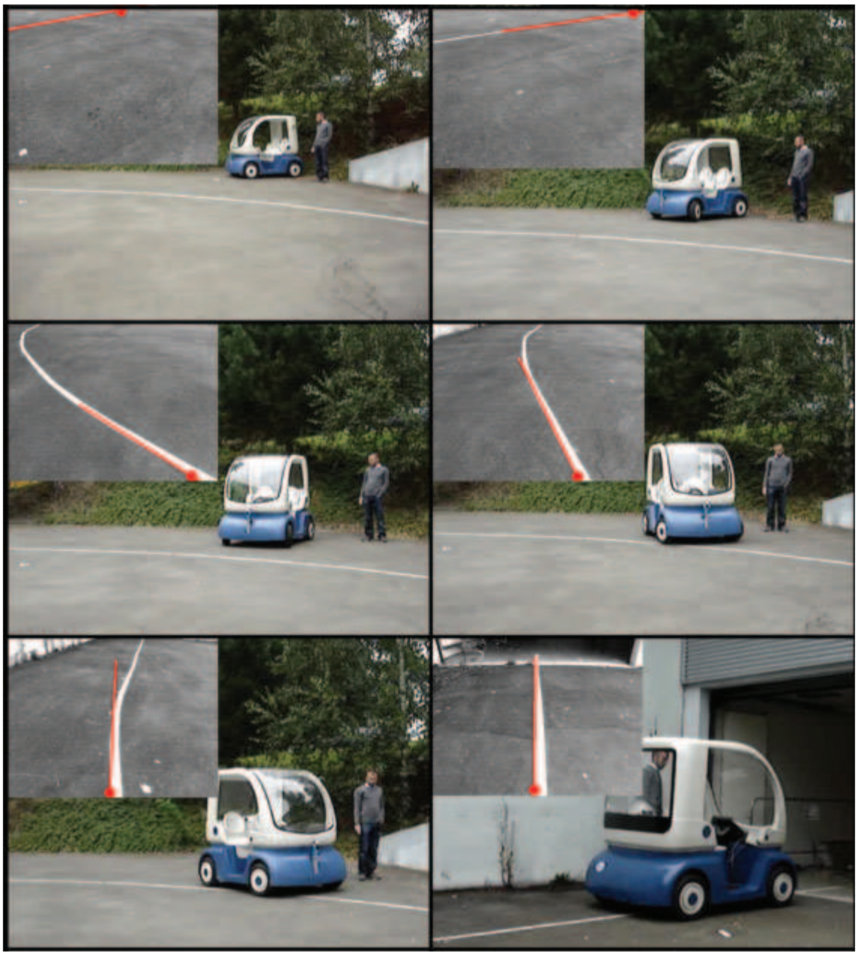


Figure 8. Line reaching and following by visual servoing

This year, we proposed a new ultrasound image-based visual servoing method to control both in-plane and out-of-plane probe motions. We made use of the image moments of the cross-section as visual features by modeling the interaction matrix relating their variation to the probe motion. Since in ultrasound the features variation depends of the object shape, we proposed in [36] to fit this latter by an ellipsoid due to its similarity to usual tumors shape. The interaction matrix was then approximated from that rough model. The cross-section image contour detection algorithm needed to compute in real time the image moments has been reported in [37]. The control scheme has been validated in both simulations and *ex-vivo* experiments performed on a motionless rabbit heart immersed in a water-filled tank.

Recently, we developed a new technique affording visual servoing without the knowledge of a 3D model of the soft tissue of interest. In that work, the interaction matrix has been exactly derived. 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 (see Fig. 9), and *ex-vivo* experiments on a motionless kidney immersed in a water-filled tank.

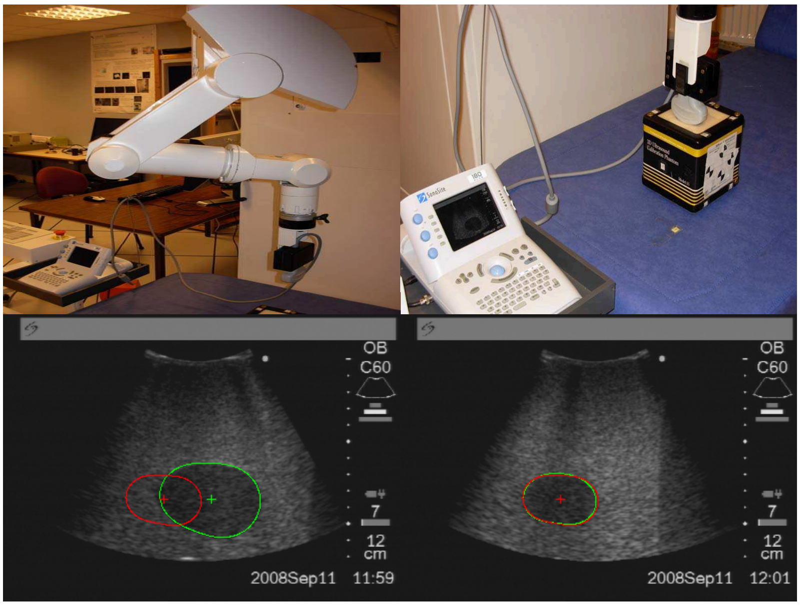


Figure 9. Ultrasound image-based visual servoing on a phantom. Objective: reach the target cross-section image (red) from an initial one (green)

6.2.2. 3D robot registration from ultrasound images

Participants: Caroline Nadeau, Alexandre Krupa.

Nowadays, different medical imaging techniques (MRI, tomography, fluoroscopy, ultrasound...) are used to visualize and capture 3D information of anatomy part of a patient in order to diagnose pathology or help the surgeon in planning a surgical intervention. This 3D information is mainly obtained from a set of 2D scans (images). In addition, segmentation and classification techniques applied on 3D raw information are used to provide a geometrical model of the considered organ. The surgeon can then use this preoperative model in order to guide his gesture during an interventional imaging procedure. The principle consists in registering the preoperative model on the patient, by the use of several 2D scans that are captured manually during the intervention with an ultrasound probe. In this context, we propose to minimize the registration error by automatically and optimally capturing 2D ultrasound peroperative images by a robotic arm holding an ultrasound probe. This work is just starting and consists in studying and developing a method that is able to optimize and automate the robot positioning in order to reach accessible 2D ultrasound scans that best minimize the registration error.

6.2.3. Motion compensation from speckle

Participant: Alexandre Krupa.

The objective of this study is to develop an ultrasound control approach that automatically synchronizes the displacement of a robotized ultrasound probe in such a way to stabilize the image of a moving soft tissue. Such a workable method could be exploited in a host of clinical applications. For example, in diagnostic ultrasound imaging, the ultrasound probe could be automatically moved to maintain the optimal view of moving soft tissue targets; or in biopsies and localized therapy procedures, needles or other surgical tools could be synchronously inserted into a moving target observed in live ultrasound. The approach we have currently developed makes only use of the speckle information contained in ultrasound images to estimate the relative displacement between a target region, that moves with the soft tissue, and the observed ultrasound image plane. Traditionally, ultrasound speckle has been considered as noise, and much effort has been devoted to remove or reduce speckle in ultrasound images. Speckle, however, is not a random noise. It results from coherent reflection of very small cells contained in soft tissue. As a result, it is spatially coherent and remains highly correlated over small motions of the ultrasound probe. In our approach, in-plane motion is handled by image region tracking and out-of-plane motion is recovered by speckle tracking using speckle decorrelation. A visual servo control scheme is then applied to manipulate the ultrasound probe to stabilize a target region in the live ultrasound image.

This concept was experimentally validated, during the sabbatical of Alexandre Krupa at the Johns Hopkins University, for rigid motion combining only two translations. This year, we extended the method and experimentally validated it for full rigid motion (3 translations and 3 rotations) on the Lagadic medical robotic platform described in Section 5.5 (see Fig. 10 and [22]).

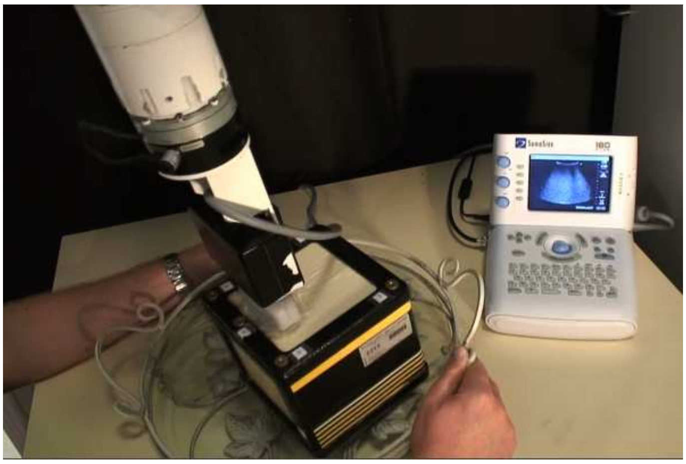


Figure 10. Automatic compensation of 6-DOF motions that are manually applied to an ultrasound phantom. The robotized ultrasound probe is controlled directly from the speckle contained in the observed ultrasound image.

6.3. Active vision

6.3.1. Find and Focus: Multi Camera Cooperation for Grasping

Participants: Claire Dune, Eric Marchand.

This study is devoted to object grasping using a manipulator within a multi cameras visual servoing scheme. The goal of this project, realized in cooperation with CEA/List (see Section 7.2), is 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. This task should be achieved with a minimum of a priori information regarding the environment and the considered object and with very few interactions with the user. Actually, the only information needed is one "click" on a global view of the scene.

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. The goal is to define camera motions that allow reducing the uncertainty on the estimated parameters. This allows the grasping module to know the localization, the orientation and the shape of the object [32].

Experiments have been conducted onto the RX90 Staubli robot arm available at the CEA-List (see Fig. 11). A method to position the gripper while taking the object shape and pose into account has been developed. This method based on the previous rough shape estimation has been compared to a method based on classical 3D reconstruction techniques. Both have been tested and validated on the RX90 robot.

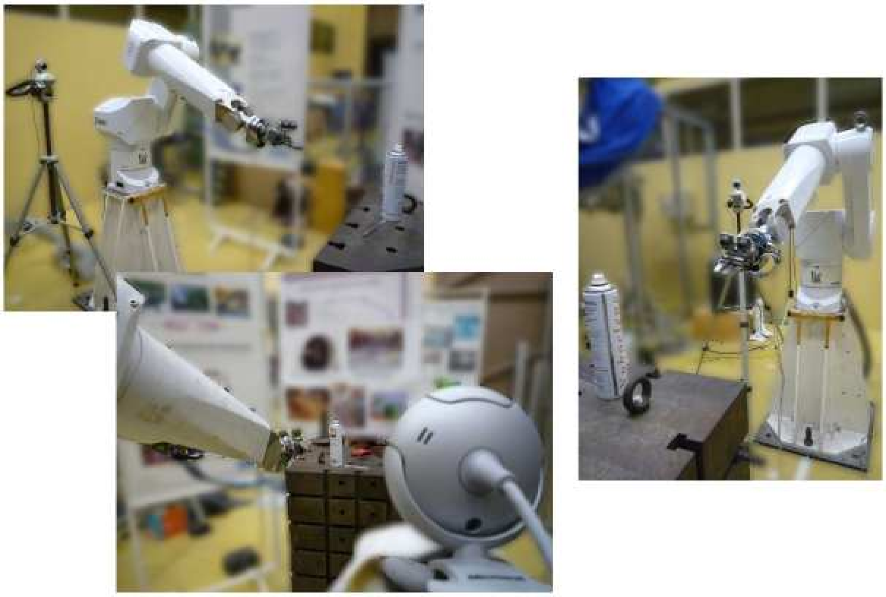


Figure 11. Find and focus: The multi camera system at CEA

6.4. Visual tracking

6.4.1. Localization for augmented reality

Participants: Fabien Servant, Jean Laneurit, Eric 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 about 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 [40]. We have extended this approach in order to consider both a camera and an inertial sensor (IMU). These techniques have been applied in a museum environment (within the ANR Gamme project, see Section 8.2.3). Automatic recognition techniques adapted to such environment have thus been also developed to bootstrap the algorithm.

6.4.2. Robust tracking for controlling small helicopters

Participants: Céline Teulière, Éric Marchand.

This study aims at developing tracking algorithms that are suitable for the control of small helicopters (X4 flyers). The work carried out this year mainly focused on maintaining a rigid link between the drone and a moving target. Since occlusions and significant appearance changes can occur during motion, the robustness of the tracking algorithm is crucial.

In order to make the tracking sensitive to different kinds of motions, while keeping a density-based representation of the object's appearance, a multiple kernels approach has been proposed. Embedded in a particle filtering framework, the resulting algorithm allows tracking the position, size and orientation of a fast moving object through frames. To decrease the number of particles necessary to achieve the tracking (and thus the computation time), the particle filter is combined with a deterministic search around the estimate of the filter.

Experiments using visual servoing considering measurements provided by this tracking method, and an estimation of the target self-motion, have been carried out on the Gantry robot (see Section 2.a), and will next be tested on the X4 flyer developed by CEA LIST. Current work aims at considering the estimation of all six degrees of freedom of target motion.

6.4.3. Robust model-based tracking for aircraft localization

Participants: Xiang Wang, Éric Marchand.

This work is realized through the European FP6 Pegase project (see Section 8.3.2). Our goal is 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 (see Figure 12).

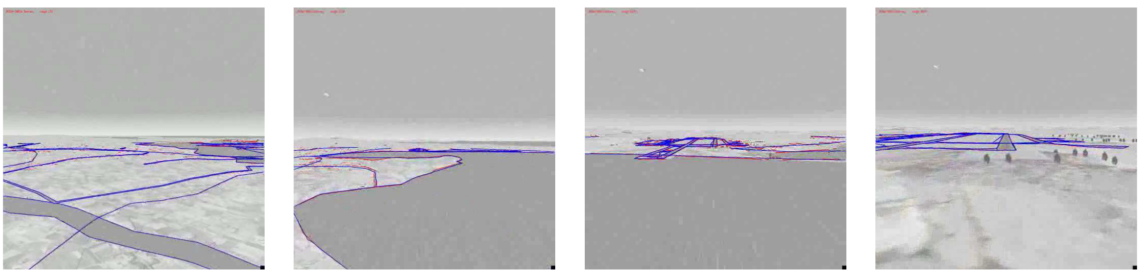


Figure 12. Localization of an aircraft using 3D model-based tracking while landing at Marignane airport.

6.4.4. Objects tracking from mutual information

Participants: Amaury Dame, Éric Marchand.

This study focuses on rigid object tracking in non-structured environment. The goal of this research is to apply the tracking method on a vehicle to position it in outdoor areas with respect to static or moving targets. One of the main problems of tracking in outdoor environment is to deal with illumination changes. As in Section 6.1.3, the approach developed is based on the information (as defined by Shannon) of the image to be robust to the illumination changes. A metric derived from information theory, mutual information, is considered. It is widely used in multi-modal image registration since it is insensitive to changes in the lighting condition and to a wide class of non-linear image transformations. Our experiments consist of selecting a plane on the initial image of a sequence. The considered warp function used is a homography allowing to get 3D information on the tracked plane. These experiments validate the robustness of the approach with respect to illumination changes.

7. Contracts and Grants with Industry

7.1. France Telecom R&D: Cifre convention

Participants: Fabien Servant, Eric Marchand.

no. Inria 2231, duration : 36 months.

This contract is 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. is to enable augmented reality on mobile devices like GSM or PDA used by pedestrians in urban environments. More precisely, its aim is 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, Eric Marchand.

no. Inria 1457, duration : 36 months.

This contract started in November 2005. It is 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 is 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 that has 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, Eric Marchand.

no. Inria 1286, duration : 36 months.

This project is 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 is a large project realized for the DGA through a consortium led by Thales Optronics. We work in close collaboration with the ARobAS team at Inria Sophia Antipolis-Méditerranée, sharing an engineer, Melaine Gautier, who participates to software developments. This project is about the development of tracking algorithms and the control of non-holonomic vehicles. Within this project, our work consists in developing 2D image-based tracking algorithms in complex outdoor scenes. The algorithms provided last year using points of interest were improved, new functionalities were 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: David Folio, 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 6.1.7.

8.2.3. ANR AM Gamme project

Participants: Jean Laneurit, Eric 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.

In this project we propose to focus on indoor environments having as a main objective the implementation of AR technologies on mobile devices. 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, Eric Marchand, François Chaumette.

no. Inria 3208, duration: 36 months.

This project, managed by Lasmea, started in July 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 will provide its expertise in the fields of 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 6.1.8.

8.2.5. ANR Psirob RobM@rket project

Participants: Guillaume Fortier, Eric 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 will be made of a PLC mobile platform of AGV type (Automatic Guided Vehicles, by BA Systèmes) and of an industrial robot arm. This platform will be 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 could 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: Alexandre Krupa, François Chaumette.

no. Inria 3585, duration: 36 months.

This project is a multidisciplinary industrial research type project led by the Prisme lab (previously called LVR) in Bourges. It is just starting in collaboration with Lirmm in Montpellier, LMS in Poitiers, CHU of Tours, and the Robosoft company. The object of this project is to develop an interactive master-slave robotic platform for a medical diagnosis application (tele-echography) and to develop a cluster of interactive functionalities combining: visual servoing, force control, haptic feedback, virtual human interface, 3D representation of organs. Within this project, we will study and develop autonomous control modes that directly make use of visual data provided by a camera observing the patient and information contained in the ultrasound image 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, has just started. 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 will consist 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 peroperative 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.

8.3. International co-operation

8.3.1. ESA/Trasys: Vimanco: Vision-based manipulation of non-cooperative objects

Participants: Eric Marchand, François Chaumette.

no. Inria 1862 and 2974, duration: 36 months.

We began in September 2005 a project for the European Space Agency. It was realized in collaboration with the Trasys company in Brussels, Galileo Avionica in Milano and KUL in Leuven. Its aim was to develop a demonstrator of a robot arm in space environment able to grasp objects by visual servoing. The considered robot is the ESA Eurobot that should be on the International Space Station in 2012. Our task in this project was to provide algorithms for objects tracking and vision-based control. This year, our contributions have been integrated on the Eurobot testbed at ESA in Noordwijk and on the Eurobot wetmodel located at Thales Alenia Space in Torino (see Figure 13).

8.3.2. FP6 Pegase

Participants: Xiang Wang, François Chaumette, Eric Marchand.

(a) (b)

Figure 13. Eurobot wet model built by Thales Alenia Space in Torino (TAS-I) (a) Eurobot in the configuration used for the VIMANCO experiments (b) View of the experiments

no. Inria 1832, duration: 36 months.

This FP6 project started in September 2006. It is managed by Dassault Aviation and groups many industrial and academic partners (Alenia Aeronautica, Eurocopter, EADS, Walphot, I3S, EPFL, ETHZ, IST, JSI). It is concerned with the automatic landing of fixed wing aircrafts and helicopters using a vision sensor. In this project, we are 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 6.4.3.

8.3.3. CNRS PICS, France-Australia

Participants: Odile Bourquardez, François Chaumette.

This international collaboration between France and Australia is supported by CNRS. It is about visual servo control of unmanned aerial vehicles. It started fall 2005 for three years. It joins Rob Mahony (Australian National University, Canberra), Peter Corke and Jonathan Roberts (CSIRO, Brisbane), Tarek Hamel (I3S, Sophia Antipolis), and our group. This year, Rob Mahony has got a short visit in our group in September 2008.

8.3.4. EA Talisker, France-US

Participants: Mohammed Marey, Roméo Tatsambon Fomena, François Chaumette.

Lagadic is involved in an Inria associate team (EA) with Prof. Seth Hutchinson from Beckman Institute at the University of Illinois at Urbana-Champaign (UIUC). In the scope of this project, Seth Hutchinson has spent a one-week visit in March, September and November 2008. Reciprocally, Mohammed Marey and François Chaumette have spent a one-week visit at Beckman Institute in May and November 2008 respectively. Roméo Tatsambon Fomena has spent a one-month visit in August 2008 to work on the visual servoing of a mobile robot using an omnidirectional vision sensor (see Section 6.1.1)

8.3.5. Visiting scientists

- Prof. Ryuata Ozawa from Ritsumeikan University, Japan, is spending a one-year sabbatical in our group from September 2008.
- Satja Lumbar from JSI in Ljubljana, Slovenia, has spent a two-weeks visit in January 2008 to work on the FP6 Pegase project (see section 8.3.2)
- Adrian Burlacu from Asachi Technical University of Iasi in Romania has spent a one-month visit in June 2008.

- Guillaume Caron from MIS in Amiens has spent a one-month visit in November 2008.
- Short visit by José-Raul Azinheira (IST Lisbon), Christoph Lampert (Max-Planck Institute, Tübingen).

9. Dissemination

9.1. Leadership within scientific community

- E. 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 was a member of the Evaluation Committee of the 2008 ANR Contint call.
- E. Marchand, C. Collewet, and F. Spindler reviewed projects for the 2008 ANR Contint call.
- F. Chaumette is a member of the Scientific Council of the GdR on Robotics.
- F. Spindler is a member of the engineers reviewing committee of the French institute for agronomy research (Inra).
- E. Marchand was a member of the Scientific Council of the Université de Rennes 1 till June 2008. He was also a member of the Administration Council of the Center for Computer Resources of the Université de Rennes 1.
- F. Chaumette was a member of the Specialist Committee of IFSIC till June 2008.
- F. Chaumette is the Head of the CUMIR at Irisa (*Commission des Utilisateurs des Moyens Informatiques*).
- *Editorial boards of journals*
  - F. Chaumette is Associate Editor of the Int. Journal of Robotics Research. He is in charge with Peter Corke (CSIRO Brisbane) and Paul Newman (Univ. Oxford) of a special issue about robot vision to appear in 2009.
  - F. Chaumette is Associate Editor of the Int. Journal of Optomechatronics. He has been in charge with Prof. Farrokh Sharifi of a special issue of this journal devoted to visual servoing [51].
- *Conference organization*
  - E. Marchand and A. Krupa are co-chairs of the organizing committee of the national conference Orasis'2009 that will be held in Tregastel in June 2009.
- *Technical program committees of conferences*
  - F. Chaumette: RFIA'08, ICRA'08, CVPR'08, RSS'08, CISA'08, ICRA'09, JNRR'09, CISA'09.
  - E. Marchand: RFIA'08, NORDIA'08, CORESA'09, JNRR'09, CVPR'09
- *Ph.D. and HdR jury*
  - F. Chaumette: Aurélien Noce (LIRMM Montpellier, reviewer), Ezio Malis (HdR, Inria Sophia Antipolis Méditerranée), Geraldo Silveira (Inria Sophia Antipolis-Méditerranée, reviewer), Joaquim Salvi (HdR, MIS Amiens, reviewer), Guillaume Allibert (LVR Orléans, reviewer).
  - E. Marchand: Benoit Louvat (INPG, reviewer), Gaël Sourimant (Université de Rennes 1)
  - A. Krupa: Ahmed Ayadi (LSIIT Strasbourg).

9.2. Teaching

- Master M2RI of Computer Science, Ifsic, Université de Rennes 1 (E. 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.
- Diic INC, Ifsic, Rennes (E. Marchand, F. Chaumette: 3D vision, visual servoing; E. Marchand, F. Spindler: programming tools for image processing).
- Insa Rennes, Electrical Engineering Dpt (F. Spindler, A. Dame: computer vision).
- Graduate student interns: L. Cadio (Diic INC, Ifsic, Rennes), Mathieu Colleaux (Diic INC, Ifsic, Rennes)

9.3. Participation in seminars, invitations, awards

- Paper [36] was one of the five finalists selected for the Best Vision Paper Award at ICRA'2008 in Pasadena in May 2008.
- Paper [37] was one of the three finalists selected for the Young Scientist Award in Robotics and Interventions at MICCAI'2008 in New York in September 2008.

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