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Project-Team LAGADIC

Visual servoing in robotics, computer vision, and augmented reality

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THEME COG

Activity Report

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2. Overall Objectives

2.1. Overall Objectives

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 the 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 [37] [5]. 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 degrees of freedom desired. 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 trajectory $\mathbf{s}^*(t)$ can also be tracked. 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 as well 2D data (coordinates of feature points in the image, moments, ...) 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 [6].

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:

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

where λ is a proportional gain that has to be tuned to minimize the time-to-convergence, $\hat{\mathbf{L}_{\mathbf{s}}}^{+}$ is the pseudo-inverse of a model or an approximation of the interaction matrix, and $\frac{\hat{\partial \mathbf{s}}}{\partial t}$ an estimation of the target velocity.

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 "cook" 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 as a linear control problem.**

Furthermore, embedding visual servoing in the task function approach [38] allows to solve efficiently the redundancy problems that appear when the visual task does not constrain all the degrees of freedom of the system. 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.

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 improvement of 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. Application Domains

Keywords: *augmented reality*, *image-guided neuro-surgery*, *robotics*, *vehicle navigation*.

The natural applications of our research are obviously in robotics. In the past, we mainly worked in the field of the grasping and of the manipulation of tools, in the field of underwater robotics for the stabilization of images, and the positioning of uninstrumented robot arms, in the field of agro-industry for the positioning of a vision sensor in order to ensure an improvement of the quality controls of agro-alimentary products, as well as in the field of the video surveillance (control of the movements of a pan-tilt camera to track mobile natural objects). More recently, we addressed the field of mobile robotics via the activities undertaken around the Cycab vehicle: detection and tracking of mobile objects (pedestrians, other vehicles), control by visual servoing of the movements of the vehicle.

In fact, researches which we undertake 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 robot 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 the control of robot arms in space, and underactuated flying robots, such as miniature helicopters and aircrafts.

In collaboration with the Visages team, we also address the field of medical robotics. The applications under consideration for the moment 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, coupling between an off-set vision of the field of examination and a force sensor for tele-operated examinations, etc.

Robotics is not the only possible application field to our researches. In the past, we were interested in collaboration with the Siames project to apply the techniques of visual servoing in the field of computer animation. It can be a question either of controlling the movement of virtual humanoids according to their pseudo-perception, or to control 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 can be related with those carried out in cogni-science, in particular in the field of psychovision (for example on the study of eye motion in the animal and human visual system, or 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, Mahandra Tallur.

Visual servoing is a very active research area in vision-based robotics. A software environment that allows fast prototyping of visual servoing tasks is then of prime interest. The main reason is certainly 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 one to propose elementary components that can be combined to build portable high-level applications. Furthermore, the increasing speed of micro-processors allows the development of real-time image processing algorithms on an usual workstation. We have developed a library of canonical vision-based tasks for eye-in-hand and eye-to-hand visual servoing that contains the most classical linkages that are used in practice. The ViSP software environment features all the following capabilities: independence with respect to the hardware, simplicity, extendibility, portability. Moreover, ViSP involves a large library of elementary positioning tasks w.r.t. various basic visual features (points, lines, circles, spheres, cylinders,...) that can be combined together, and an image processing library that allows the tracking of visual cues (dot, segment, ellipse, spline,...). A simulation software has also been developed.

Primarily developed for Unix workstations, this year was devoted to extend ViSP under Windows by adding framegrabbing and display functionalities. The CMake tool was introduced to insure the multi platform build process. To improve the software quality, daily builds have been deployed considering different compilers and

OS. A Dart server was installed to synthesize the testing results. Moreover, ViSP migrates on Inria's forge to provide a complete development environment. ViSP and its full functionalities are described in [9]. A new version was released and is available from http://www.irisa.fr/lagadic/visp. Since ViSP open source code is available under Windows, it has been downloaded and used in research labs in China, Hungary, Portugal, Spain and France.

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. Tracking objects in the scene requires to computing 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 are given for different features including 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 is 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. More recently, we also considered the case of non-rigid objects. The proposed method has been validated on several complex image sequences including outdoor environments. Application for this tracker is robotics and visual servoing as well as augmented reality applications.

5.4. Development work: Robot vision platforms

Participant: Fabien Spindler.

We exploit several experimental platforms to validate our research work in visual servoing and in active vision. More precisely, we have two robotic systems built by Afma Robots in the 90 years. The first one is a cartesian robot with six degrees of freedom, the other one is a cylindrical robot with four degrees of freedom. These robots are equipped with cameras mounted on the effector. Depending on the application, it could be either a classical CCD camera with or without wireless video transmission which are associated to an Imaging Technology framegrabber, or a Marlin firewire camera. A PC on Linux communicates with the robot using a SBS Technologies bus adapter. 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.

Before the end of the year, all the drivers (Imaging Technology framegrabber, firewire camera, SBS Technologies bus adapter) and developments around these two platforms will migrate from Fedora 1 to Fedora 5 Linux environment to provide an up to date and more powerful system.

5.5. Development work: Medical robot

Participant: Fabien Spindler.

To validate our research in the medical robotics field, since 2004 we exploit a six degrees of freedom arm designed by Sinters company. This robot is equipped with an ultrasound probe. The beginning of this year was devoted to perpetuate the software of the automatic probe calibration application by introducing some parts in our ViSP visual servoing library.

During Alexandre Krupa's sabbatical at Johns Hopkins University no new developments were made on this platform.

5.6. Development work: Cycab

Participants: Fabien Spindler, Albert Diosi.

The Cycab is a small four wheel drive autonomous electric car dedicated to vision-based mobile robotics applications. 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. This year, a vision-based navigation scheme was implemented on the Cycab [36]. It allows to follow a visual path by autonomous navigation in outdoor urban environments using only monocular vision. Moreover, a video was achieved to present the navigation results. It is available from Lagadic's web site.

6. New Results

6.1. Visual servoing

6.1.1. Geometric visual features modeling

Participants: Romeo Tatsambon, François Chaumette.

This study is directly related to the search of optimal visual features, as described in Section 3.1. Following our past works on selecting adequate combination of image moments as visual features for visual servoing [1], we have considered a spherical projection model to search for optimal visual features for visual servoing. A high motivation to use this projection model is its simplicity compared to the complex equations generated by the omnidirectional projection models. Using this projection model, a new minimal set of three visual features has been proposed for visual servoing from spheres using any central catadioptric system (and thus classical perspective cameras). The interaction matrix related to those features is maximally decoupled and presents a linear link between the visual features and the translational velocities. Using the proposed visual features, a classical control method has been proved to be globally stable even in the presence of modeling error (on any catadioptric system) and locally stable to calibration errors on perspective cameras. Experimental results obained with a simple ball have been used to validate the proposed theoretical results with perspective cameras. Future works will be devoted to search for similar results for other geometric primitives such as straight lines for instance.

6.1.2. Photometric features modeling

Participants: Eric Marchand, Christophe Collewet.

One of the main problem in visual servoing is to extract and track robustly the image measurements that are used to build the visual features involved in the control scheme. This may lead to complex and time consuming image processing, and may increase the effect of image noise. To cope with this problem, we propose to use directly photometric features, as the luminance for example, as input of the control scheme. As described in Section 3.1, the main challenge is to obtain the interaction matrix related to such features. This requires the knowledge of a photometric model to account for illumination changes caused by a relative camera/object motion and (or) a relative object/lighting sources motion. From realistic estimated models [23], [24], [22] this interaction matrix should be derived. First results have been obtained in the simple case of Lambertian scenes. We have also proposed an original approach to control camera position and/or lightning conditions in an environment using image gradient information. Our goal was to ensure a good viewing condition and good illumination of an object to perform vision-based task (recognition, tracking, etc.). Within the visual servoing framework, we have proposed solutions to two different issues: maximizing the brightness of the scene and maximizing the contrast in the image. Solutions have been proposed to consider either a static light and a moving camera, either a moving light and a static/moving camera. The proposed method is independent of the structure, color and aspect of the objects. Simulation results have also shown that positioning tasks can be achieved.

6.1.3. Vision-based tasks sequencing

Participants: Nicolas Mansard, François Chaumette.

The objectives of this study are to realize global and high level robotics tasks by adequately sequencing a set of reactive vision-based tasks. Indeed, visual servoing techniques are very efficient for numerous types of robotic problems. However, the control can become difficult or even erratic when the displacement to be realized is large. Moreover, only links between the camera and the tracked visual features are taken into account in the control law. To integrate the servo into a real complex robotic system, the control should also make sure that it avoids undesirable configurations such as articular joint limits, obstacle or visual occlusions. Our research work is mainly focused on a reactive way to solve this problem.

For that, we have proposed a high-level execution controller that enables or disables some parts of the global control law to ensure global convergence and obstacle avoidance [11]. The key idea is to divide the global full-constraining task into several subtasks that can be applied or inactivated to take into account potential constraints of the environment. Far from any constraint, the robot moves according to the full task. When it comes closer to a configuration to avoid, a higher level controller removes one or several subtasks, and activates them again when the constraint is avoided. The last controller ensures the convergence at the global level by introducing some look-ahead capabilities when a local minimum is reached. The robot accomplishes the global task by automatically sequencing sensor-based tasks, obstacle avoidance and short deliberative phases.

This approach has been applied to a humanoid robot through a collaboration with Olivier Stasse and Kazuhito Yokoi from the AIST/CNRS Joint Robotic Laboratory of Tsukuba, Japan. The goal of this collaboration was to show that the task sequencing approach is an interesting solution for complex-robot control. For such robots, closed loop control such as visual servoing is very appealing to simplify the complexity of the computations and to improve the robustness to the huge number of calibration parameters. We have shown the validity of the approach by realizing a grasping task while walking. The experimentation have been realized on the HRP-2 humanoid robot platform, in Tsukuba.

6.1.4. Qualitative visual servoing and varying-feature-set control laws

Participants: Anthony Remazeilles, Nicolas Mansard, François Chaumette.

As mentioned in Section 3.1, classical visual servoing control laws are designed so that the current visual features $\mathbf{s}(t)$ reach a desired value $\mathbf{s}^*$. Nevertheless, obtaining exactly a desired value is a strong constraint that may be useless in some applications. For example, if an object tracking task is just specified as keeping the image of the object within the camera field of view, it is not necessary to require the center of gravity of this object to project exactly in the center of the image. Indeed, it is sufficient to ensure that the center of gravity belongs to an area around the center of the image.

For such a purpose, we have developed a new approach, named qualitative visual servoing, which ensures that the current feature reaches a confident interval defined in the vicinity of $\mathbf{s}^*$, that is such that $\mathbf{s}(t) \in [(1-p)\mathbf{s}^*, (1+p)\mathbf{s}^*]$ where scalar p defines the size of the interval. When a feature reaches the confident interval, it is not considered any more in the control law in order to avoid any disturbance on the remaining features, and to simplify the control process. Such qualitative visual features can be combined with classical ones, if needed. As first experiments, it has been used to enforce points to stay within the camera field of view during classical image-based positioning tasks [35].

When applying such a control scheme, the error-vector dimension changes during the servoing (each time a qualitative feature enters or leaves the confident interval). In this meaning, this method is similar to some other control schemes that we refer as varying-feature-set control laws. We have shown that such control laws are not always continuous when the error-vector dimension changes. Based on this observation, we have proposed a new control law that can generalize the task-function approach to the varying-feature-set control laws and thereby ensures the continuity even at dimension change. This new control law is also compliant with the redundancy formalism [11].

This solution has then been applied for joint-limit avoidance during a visual servoing. The joint-limit avoidance behavior is written as a qualitative task. Using the redundancy formalism, the avoidance is set as a task having priority over the visual servoing, which ensures that the joint limits will be avoided during the servo.

6.1.5. New control laws for visual servoing

Participants: Mohammed Marey, François Chaumette.

This new study started in October 2006. Its objective is to design new control schemes to improve the behavior of visual servoing whatever the choice of the selected visual features. In a first part, we have designed a new control scheme which is globally asymptotically stable but for non attractive local minima. We are currently studying its full properties and comparing its behavior with respect to the classical control schemes.

6.1.6. Navigation from a visual memory

Participants: Anthony Remazeilles, Sinisa Segvic, Albert Diosi, François Chaumette.

In this research, visual path following in outdoor urban environments using only monocular vision is investigated. Vision systems for outdoor navigation face many challenges such as:

- The appearance of objects may change due to different imaging conditions (viewing position, illumination, exposition time).
- Landmarks used for navigation may be temporarily occluded by moving objects.
- Objects in shadow or in bright sunlight may not be visible due to the insufficient dynamic range of the sensor.
- Motion blur, image noise, sun shining into the camera, etc..

Our navigation framework developed in this project alleviates some of the aforementioned problems and provides stable interest points in current and reference images for image-based visual servoing.

The first part in the framework involves teaching the robot a reference path i.e. mapping. The map is represented by a set of reference images together with 3D and 2D coordinates of point feature landmarks extracted from the reference images. During teaching the robot is manually driven on a reference path while images from a camera mounted on the robot are captured and saved. Then the saved images are processed offline during which reference images with corresponding points features (interest points) are selected and the local 3D geometry of points shared between neighboring reference image pairs are reconstructed. The 3D reconstruction improves robustness during navigation by enabling the reprojection of just previously occluded features and the checking of the consistency of associated points. We are also able to perform mapping online, albeit at more modest vehicle velocities.

The second part in the framework involves navigation. Here the robot is first localized in the map by matching the current image from the camera to a reference image specified by the user. Matched features are then tracked as the robot moves along the path. The tracked features are used for local 3D reconstruction which enables feature reprojection and consistency checking. Further, the tracked features are used to control the robot's motion using image based visual servoing to follow the reference path. During navigation, robustness against changing illumination is ensured by compensating the contrast of tracked image patches.

We have carried out numerous experiments using our CyCab in different environments and lighting conditions. We have conducted successful autonomous navigation experiment with vehicle velocities up to 1.2m/s, and paths up to 740m.

Our initial concept with simulation results was published in [34]. Vision system implementation details can be found in part in [36].

6.1.7. Control of aircrafts by visual servoing

Participants: Odile Bourquardez, François Chaumette.

This study aims at developing visual servoing techniques for the control of the motions of aircrafts. As for fixed wing aircrafts, the considered applications are automatic landing, take off, and in-flight refueling. This year, we have concentrated our works on the two first tasks. Visual features based on the measurements that can be extracted from the image of the runway (typically, its border lines and start and end limits) have been modeled. A flight simulator provided by Dassault Aviation has been coupled to the visual servoing simulation software included in ViSP. The airplane dynamics model which links the pilot inputs and the aircraft motions have also been provided by Dassault Aviation. Using a linearized version of this model and decoupled visual features, an image-based control law has been designed to align the airplane with respect to a runway. Current works are devoted to apply this control scheme in an automatic take-off and landing application.

As for helicopters, we have designed and compared 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 feature and control scheme so that the sensitivity to any translational motion was the same [20]. We have also implemented kinematic image based visual servoing on the X4-flyer developed at CEA-List within the Robvolint project (see Section 8.2.1). It uses a miniature camera, with wireless video transmission, mounted on the X4-flyer. We have experimented the control laws proposed in [20] and compared the results with more classical visual servoing scheme using perspective zeroth and first order moments. The visual features from [20] have the passivity property, which is very interesting to ensure desirable theoretical properties when designing control laws for the X4-flyer. Real experiments have shown that this property is not a critical issue in practice, since better behaviour has been obtained with the perspective zeroth and first order moments.

6.2. Medical robotics

6.2.1. Robotized 3D ultrasound imaging

Participants: Alexandre Krupa, François Chaumette.

Performing three-dimensional ultrasound imaging with a conventional two-dimensional probe consists of capturing a set of ultrasound images with their respective locations in order to position them in a 3D reference frame. Usually the clinician performs the 3D acquisition manually through the use of an optical or magnetic localization system which provides continuously the position of the probe. However free-hand motion may generate probe trajectory or soft tissue deformation which are not suitable for accurate 3D reconstruction. Reverse motions of the probe usually introduce large position errors of the image plane and variation of the force applied to the patient skin implies soft tissue deformations. Therefore we have proposed to use a robotic system to automatically move the ultrasound probe along a given trajectory on the patient skin, measure the probe location and control the force applied to the patient. As for 3D free-hand ultrasound imaging, the spatial parameters of the probe have to be calibrated. The calibration method that we use consists of positioning, with several orientations and translations, the ultrasound image plane on the intersection point of a cross-wire phantom immersed in a box of water. This procedure was automated thanks to a visual servoing technique [] based on 2D ultrasound images and experimentally validated on our medical robotic platform by performing accurate 3D reconstructions of a medical phantom along a desired trajectory [26].

6.2.2. Ultrasound image-based visual servoing

Participants: Rafik Mebarki, Alexandre Krupa.

The main aspect of this research work is to develop new visual servoing techniques based on ultrasound images in order to control directly the motion of robot for medical applications. An important research issue is to control the motion of the probe in the 3D space by using only a 2D slide of the environment. The main difficulty is that only information inside the observation plane is available and we have to develop new strategies to cope with this problem. In the literature, very few research works have dealt with the control of degrees of freedom (DOF) outside the ultrasound plane by visual servoing based on ultrasound images. In most works only a maximum of three DOF (2 translations and 1 rotation) in the image plane are controlled. Therefore in order to control the motion outside the ultrasound image plane, we have proposed in [19] to use a geometrical model of the object interacting with the ultrasound image plane. This approach allows to determine the variation of ultrasound visual features with respect to the displacement of the probe. In this preliminary study we have considered that the object of interest interacting with the ultrasound probe is a tumor that could be modeled by an egg shaped object whose geometrical parameters are previously estimated from 3D ultrasound imaging. Moreover, the contour of the tumor extracted from the image is chosen as the visual feature. The proposed robotic task consists to automatically position the ultrasound probe in order to reach a desired 2D view of the tumor. This may be useful for example to position automatically the ultrasound image on the center of the tumor for medical applications such as biopsy or tumor ablation. As simulation results were promising, we plan to experimentally validate this new approach on our robotic platform.

6.2.3. Motion tracking in ultrasound

Participant: Alexandre Krupa.

This new study has been started by Alexandre Krupa during his research sabbatical in the Computer-Integrated Surgical Systems and Technology Engineering Research Center at the Johns Hopkins University of Baltimore. It concerns the tracking of physiological motion from 2D ultrasound images. The objective is to track in real-time the full motion (3 translations and 3 rotations) of a soft tissue of interest which moves due to the breathing and heart beating. One of the possible medical applications is to synchronize by visual servoing the displacement of an ultrasound probe held by a medical robot with a moving organ/tumor or to track a moving target by a surgical tool. This can also be useful to perform 3D imaging of moving organs without obtaining artefact effects induced by the physiological motion. The difficulty concerns the detection of the elevation motion which corresponds to the displacement of soft tissue along the orthogonal direction of the observation plan. In our approach we use the speckle contained in the ultrasound image as visual feature in order to extract the out-of-plane and in-plane motion. Usually, the speckle is considered as a noise in the image and several research works have been done to reduce it. However, the speckle is not a random noise but instead is highly correlated over small motion of the probe.

6.3. Active vision

6.3.1. Structure from motion

Participants: Christophe Collewet, François Chaumette.

Synthetizing an image-based control law requires usually a model of the scene observed by the camera and also the knowledge of the desired features. In some cases they are unknown, let us cite for example applications in surgical domain or in unknown environments like underwater or space.

Classically, visual servoing approaches cannot cope with such applications. Therefore, we have proposed to perform a 3D reconstruction phase during the servoing step either by a *continuous* or by a *discrete* approach. The former is based on the knowledge of the optical flow, thus on the instantaneous velocity, and consequently implicitly assumes that the acquisition rate is high. The latter one does not require this assumption since displacements rather than instantaneous velocities are considered, thus they are based on matching visual features between two (or more) views. More precisely, we have proposed to recover the parameters of the tangent plane at a certain point of the object and introduce them in a control law to perform a positioning task. Our approach is based on the computation of the 2D displacement between two consecutive frames contrary to other approaches where, either the current and the desired frames are required or a features matching between two consecutive frames is needed, as for discrete approaches. Consequently, our technique enlarges the application domain of visual servoing to complex scenes as, for example, natural scenes where matching is known to be a difficult task. Our algorithm is based on an unified 2D displacement model to cope as well with planar as with non-planar objects. To our knowledge, previous works always required explicit constraints about the scene or used complex selection models mechanisms. However, since our unified motion model is only an approximation of the true one, we have proposed two ways to enlarge its domain of validity.

The first one is based on active vision and can be used in the continuous case leading to a linear formulation. Theoretical issues have shown that $v_z = 0$ (the translation velocity along the optical axis) minimizes the modeling error between the true and the approximated motion models. Besides, experiments on various objects (plane, cylinder and sphere) have validated that better results are obtained, whatever the shape of the object is, when active vision is used (i.e. $v_z = 0$). Nevertheless, when the curvature of the object (like a sphere of radius 7 cm) and the desired orientation are high (around 20 degrees), we have seen that a bad positioning could be obtained.

The other one is based on the selection of points involved in the computation of the 2D displacement. Indeed, we have proved that there is always a locus where the difference between the true and the approximated displacement models vanishes. To select the points, M-estimators have been introduced. Experiments have shown that this approach leads to better results than when using active vision but requires the use of a discrete approach to be really effective since a low acquisition rate is obtained (around 400 ms). Therefore, only slow camera motions can be considered. It can be considered as the main drawback of this approach. In contrast, the computation cost of using active vision is low (around 280 ms) and thus higher 3D velocities can be reached.

To conclude, these works allow to achieve very accurate positioning tasks on unknown object (the orientation error is lower than 1 degree).

6.3.2. Visual SLAM

Participants: Fabien Servant, Eric Marchand.

This new study focuses on real-time augmented reality for mobile device. It is related to France Telecom contract presented in Section 7.2. 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 (using Visual SLAM) 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. This year, first experiments related to monocular visual localization have been carried out. Since the camera is supposed to move within a urban environment, planar constraints have been introduced within the localization algorithm.

6.3.3. Find and Focus: Multi Camera Cooperation for Grasping task Cooperation

Participants: Claire Dune, Eric Marchand.

This study is dedicated 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 7.3), is to allow disable persons to grasp an object with the help of a robot arm mounted on their wheel chair. 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.

To control the manipulator, two cameras have been added to the robotic system: one is fixed on the top of the wheelchair (eye-to-hand), it gives a wide view of the scene, the other is mounted on the end effector of the arm (eye-in-hand), it allows to see purposively some details of the scene. We have first focused on an initialisation step for an hybrid eye-in-hand/eye-to-hand to guarantee that the object of interest is in both fields of view. Assuming that the object of interest is within the deported camera field of view, it may not be within the eye-in-hand one. 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. This method has been tested and validated on a multi view robotic system.

6.4. Visual tracking

6.4.1. Tracking by matching

Participants: Thi Thanh Hai Tran, Éric Marchand.

A fully automated tracking system requires to automatically initialize camera pose and re-initialize it whenever objets of interest get lost. For real-time applications, this process needs to be done as quickly as possible. We approach this problem by using image matching technique. This takes advantage of the fact that for pose estimation purpose, several training images may be available while having markers is not always possible. Image matching allows to determine the displacement between the current camera and the reference one.

Matching two images consists of 3 steps: (1) detect keypoints from each image; (2) project keypoints into eigenspace; (3) search for the nearest neigbor in eigenspace. Keypoints are points of interest in image where the signal image changes significantly. We propose a very simple but efficient method to detect keypoints from grey-scale image. It provides stable points representing mostly physical corners of objects in the scene. Each keypoint is then assigned one or some canonical orientations which are local maxima of histogram of gradient orientations. A gradient magnitude based descriptor is then computed on a local region (i.e. a patch of size 17x17) centered at a keypoint, in its canonical orientation. To reduce dimensions of feature space, PCA technique is used to build an eigenspace. The search for the nearest neighbor in eigenspace is carried out by using an approximative nearest neighbor searching technique (ANN).

The proposed matching method has been tested in a visual servoing application, in which the corresponding keypoints are provided to build a control law in order to move the robot from a given position to a desired position. It runs at 10-14Hz and gives very satisfactory result. Moreover, experiments showed a very attractive property of the method: it can automatically re-initialize when the scene is partly or completely occluded.

6.4.2. 3D model-based tracking using multiple cameras

Participants: Fabien Dionnet, Éric Marchand.

A real-time, robust and efficient 3D model-based tracking algorithm for a monocular vision system has been developed over the three last years. Tracking objects in the scene requires to compute the pose between the camera and the object. Non-linear pose computation is formulated by means of a virtual visual servoing and statistically robust estimation techniques have been introduced in the control law [16]. We have extended this algorithm to handle input from multiple cameras with small or large baseline. Considering the link between the two cameras, visual information from the two images are used in the same minimization process to compute the global position of the system [21]. Experimental results have been obtained using particular objects that can be found on the International Space Station (see Section 7.4.1).

6.4.3. 3D model-based tracking with an omnidirectional camera

Participants: Éric Marchand, François Chaumette.

Increasing the field of view of vision sensors is an important practical issue in robot vision. One solution is to consider catadioptric camera that allows a 360° field of view. In this study we have proposed a 3D model-based tracking algorithm that allows a fast and reliable tracking of 3D objects within central catadioptric images. The proposed approach relies on the virtual visual servoing approach we have developed in the recent years [8],[16]. All the modeling aspects have been reconsidered to consider this projection model. The proposed approach has been proved to be fast and reliable and can therefore be considered in various robotics applications such as visual servoing.

6.4.4. 3D model-based hybrid tracking

Participants: Muriel Pressigout, Éric Marchand.

We have developed a real-time, robust and efficient 3D model-based tracking algorithm. Extending the previous contour based method [16], a non linear minimization approach has been proposed to register 2D and 3D cues for monocular 3D tracking. This approach fuses a 3D model-based approach based on edges tracking and a temporal matching relying on the texture analysis into a single non-linear objective function. Indeed, estimating both pose and camera displacement introduces an implicit spatio-temporal constraint that the simple 3D model-based tracker was not able to consider. Furthermore, fusing measurements based on texture and edges improves the robustness of the tracking.

This year we have extended our previous work in two directions: first we have considered not only piecewise planar objects (polyhedral objects) but also non-planar objects [33]. Then, since texture is considered, it is also important to be robust to large illumination changes. Different illumination models have thus been studied. Many works already deal with the problems raised by changes in illumination for patch tracking: from classical approaches assuming a perfect conservation of luminance to more sophisticated methods based on the photometric model [32]. We also began a new study that considers another hybrid approach with both contour information and optical flow [12].

7. Contracts and Grants with Industry

7.1. France Telecom R&D: Augmented reality in urban environment

Participants: Tran Thi Thanh Hai, Eric Marchand.

no. Inria 1263, duration : 18 months.

This contract started in October 2005. The goal of this project is to evaluate the capability of the 3D visual tracking algorithm we have developed in the recent years [7],[16] to handle rough models provided by geographic information systems. A second part of this project is concerned with the automatic initialization of the tracking process using matching algorithms (see Section 6.4.1).

7.2. France Telecom R&D: Cifre convention

Participant: Eric Marchand.

duration : 36 months.

This contract is dedicated to support the Cifre convention between France Telecom R&D and Irisa regarding Fabien Servant's Ph.D. (see Section 6.3.2). The goal of the Ph.D. is to enable augmented reality on mobile devices like GSM or PDA used by pedestrians in urban environments. Using a camera and external sensors, the goal of this study is to compute the absolute pose of the camera to show to the end-user geolocalized information in an explicit way.

7.3. 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 (see Section 8.1.1) through a grant to Claire Dune for her Ph.D. ("krog" means grasping in the Breton language). It is dedicated to object manipulation by visual servoing. 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.

7.4. European initiatives

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

Participants: Fabien Dionnet, Eric Marchand, François Chaumette.

no. Inria 1862, duration : 24 months.

We began in September 2005 a project for the European Space Agency. It is realized in collaboration with the Trasys company (Brussels), Galileo Avionica (Milano) and KUL (Leuven). Its aim is 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 2008. Our task in this project is to provide algorithms for objects tracking and vision-based control. The work described in Section 6.4.2 has been realized within this project.

7.4.2. FP6 Pegase

Participants: François Chaumette, Eric Marchand.

no. Inria 1832, duration : 36 months.

This FP6 project started in September 2006. It is managed by Dassault Aviations. It is concerned with the automatic take off and landing of fixed wing aircrafts and helicopters. In this project, we are the leader of the workpackage devoted to visual tracking and visual servoing.

7.5. French national programme Predit

7.5.1. Mobivip project

Participants: Anthony Remazeilles, Sinisa Segvic, François Chaumette.

no. Inria 558, duration : 36 months.

This project is a large project headed by Inria Sophia Antipolis. It is concerned with the navigation of mobile vehicles in urban environments. Within this project, our work consists in designing autonomous vision-based navigation techniques using an image database of the environment (see Sections 6.1.6). As for scientific aspects, this project is closely related to the Robea Bodega project described in Section 8.2.1.

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 contract started in November 2005 (“krog” means grasping in the Breton language). It is also supported by the CEA (see Section 7.3). It is dedicated to object manipulation by visual servoing. 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.

8.2. National initiatives

8.2.1. Robea Robotics research programme

- *Egocentre project*
  Participants: Nicolas Mansard, François Chaumette.
  This three-years project, started in September 2003, aims at developing task sequencing schemes to realize high level robotics tasks from local sensor-based control techniques. It involves a collaboration between Laas and Cerco in Toulouse, Enit in Tarbes, and our team. Nicolas Mansard’s PhD is realized in the scope of this project (see Section 6.1.3).

- *Bodega project*
  Participants: Anthony Remazeilles, Sinisa Segvic, François Chaumette.
  This two-years project, ended in April 2006, aimed at designing vision-based and sensor-based methods for the autonomous navigation of mobile vehicles moving around an urban environment. It involved a collaboration between Ensil in Limoges, UTC in Compiègne, Lasmea in Clermont-Ferrand, the Icare team of Inria Sophia-Antipolis, and our team. Works described in Section 6.1.6 have been achieved within this project.
- *Robvolint project*
  Participants: Odile Bourquardez, François Chaumette.
  This two-years project, ended in April 2006, aimed at developing vision-based localization techniques and visual servoing schemes for small helicopters moving around an indoor environment. It involved a collaboration between I3S in Nice, CEA in Fontenay-aux-Roses, Ircynn in Nantes, and our team. Works described in Section 6.1.7 about helicopters have been realized within this project.

8.3. Bilateral international co-operation

8.3.1. 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), Vincent Moreau (CEA-List, Paris) and our group. Odile Bourquardez spent a one month visit and François Chaumette a one week visit in Brisbane and Canberra in November 2006.

8.3.2. Visiting scientists

- Short visit by Seth Hutchinson (The Beckmann Institute, Urbana-Champaign), Danica Kragic (KTH Stockholm), Darius Burshcka (München University), Ville Kyrki (Lappeenranta University of Technology, Finland), Vincent Lepetit (EPFL, Lausanne), Luigi Villani (University of Napoli), José Santos-Victor (IST, Lisbonne), Abderrahmane Kheddar (AIST/CNRS JRL, Tsukuba).

9. Dissemination

9.1. Leadership within scientific community

- F. Chaumette was a member of the CNRS Experts Committee on Robotics, in charge of the prospective in this field.
- F. Chaumette was a member of the Evaluation Committee of the 2006 ANR Psirob call devoted to robotics.
- F. Chaumette has participated to the creation of the GdR on Robotics as a member of its board.
- E. Marchand is a member of the Scientific Council of the University of Rennes 1.
- E. Marchand evaluated projects for the 2006 ANR MDCA (Masse de données et connaissances ambiantes) call and for the University Louis Pasteur in Strasbourg (BQR).
- E. Marchand is a member of the Administration Council of the Center for Computer Resources of the University of Rennes 1
- E. Marchand organized with Ezio Malis (Inria Sophia-Antipolis) a thematic one day workshop about robust real-time tracking for the GDR ISIS.

- F. Spindler is a member of the engineers reviewing committee of the French institute for agronomy research (INRA).
- F. Spindler was a member of the recruitment jury for two engineers positions (IE) at INRA.
- F. Chaumette is a member of the Specialist Committee of IFSIC. He is also the Head of the CUMI at Irisa (*Commission des Utilisateurs des Moyens Informatiques*).
- *Technical program committees of conferences*
  - F. Chaumette: ICRA'2006, ECCV'2006, CVPR'2006, IROS'2006, ICRA'2007.
  - E. Marchand: ECCV'2006, AMDO'2006, Deform'2006, Orasis'2007, JNRR'2007.
- *Ph.D. and HdR jury*
  - F. Chaumette: Nicolas Andreff (HdR, Lasmea, reviewer), Ryad Benosman (HdR, Paris 6, reviewer), Guillaume Morel (HdR, Paris 6, reviewer), Eric Royer (Ph.D., Lasmea, reviewer), Hicham Hadj Abdelkader (Ph.D., Lasmea, reviewer), Selim Benhimane (Ph.D., Inria Sophia-Antipolis, reviewer), Mickael Sauvéee (Ph.D., Lirmm, reviewer).
  - E. Marchand: Tran Thi Thanh Hai (Ph.D., Inria Rhône-Alpes, INPG), Flavio Vigueras (Ph.D., Loria, reviewer)

9.2. Teaching

- Master M2RI of Computer Science, Ifsic, University of Rennes 1 (E. Marchand): 3D Computer vision.
- Diic INC, Ifsic, University of Rennes 1 (E. Marchand, F. Chaumette: 3D vision, visual servoing; E. Marchand, F. Spindler: programming tools for image processing).
- Insa Rennes, Electrical Engineering Dpt (E. Marchand, F. Spindler, R. Tatsambon: computer vision, C. Collewet: seminar about visual servoing on unstructured objects: applications to the agri-food industry).
- University of Siena, Ph.D. course on visual servoing (F. Chaumette)
- Graduate student interns: N. Lemasson (Master LSIIT, Strasbourg), Bruno Renier (INSA, Rennes).

9.3. Participation in seminars, invitations, awards

- N. Mansard has got a grant to spend two months in Tsukuba at the CNRS/AIST JRL to work on humanoid robots in July and August 2006.
- Paper [] has been selected for a special issue of Advanced Robotics devoted to the best papers of IROS'2005.

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