IN PARTNERSHIP WITH:
CNRS

Institut national des sciences appliquées de Rennes

Université Rennes 1

Activity Report 2014

Project-Team LAGADIC

Visual servoing in robotics, computer vision, and augmented reality

IN COLLABORATION WITH: Institut de recherche en informatique et systèmes aléatoires (IRISA)

RESEARCH CENTERS
Rennes - Bretagne-Atlantique
Sophia Antipolis - Méditerranée

THEME
Robotics and Smart environments

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Project-Team LAGADIC

Keywords: Visual Servoing, Tracking, Slam, Computer Vision, Robotics, Intelligent Transportation System, Augmented Reality

Creation of the Project-Team: 2004 December 06.

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2. Overall Objectives

2.1. Overall Objectives

Historically, research activities of the Lagadic team are concerned with visual servoing, visual tracking, and active vision. Visual servoing consists in using the information provided by a vision sensor to control the movements of a dynamic system. 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 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. Our objective is thus 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 (see Section 4.1). 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) through the visual servoing approach.

Thanks to the arrival of Patrick Rives and his students in the group in April 2012, which makes Lagadic now localized both in Rennes and Sophia Antipolis, the group now also focuses on building consistent representations of the environment that can be used to trigger and execute the robot actions. In its broadest sense, perception requires detecting, recognizing, and localizing elements of the environment, given the limited sensing and computational resources available on the embedded system. Perception is a fundamental issue for both the implementation of reactive behaviors, as is traditionnaly studied in the group, and the construction of the representations that are used at the task level. Simultaneous Localization and Mapping (Slam) is thus now one of our research areas.

Among the sensory modalities, computer vision, range finder and odometry are of particular importance and interest for mobile robots due to their availability and extended range of applicability, while ultrasound images and force measurements are both required for our medical robotics applications. The fusion of complementary information provided by different sensors is thus also a central issue for modeling the environment, robot localization, control, and navigation.

Much of the processing must be performed in real time, with a good degree of robustness so as to accommodate with the large variability of the physical world. Computational efficiency and well-posedness of the methods developed are thus constant preoccupations of the group.

3. Research Program

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 [1]. 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. 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, ...) 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.

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:

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

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. It is thus extremely important to design adequate visual features for each robot task or application, the ideal case (very difficult to obtain) being when the corresponding interaction matrix is constant, leading to a simple linear control system. To conclude in few words, **visual servoing is basically a non linear control problem. Our Holy Grail quest is to transform it into 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. 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.

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. If fiducial markers may still be useful to validate theoretical aspects in modeling and control, natural scenes with non cooperative objects and subject to various illumination conditions have to be considered for addressing large scale 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.

3.3. Slam

Most of the applications involving mobile robotic systems (ground vehicles, aerial robots, automated submarines,...) require a reliable localization of the robot in its environment. A challenging problem is when neither the robot localization nor the map is known. Localization and mapping must then be considered concurrently. This problem is known as Simultaneous Localization And Mapping (Slam). In this case, the robot moves from an unknown location in an unknown environment and proceeds to incrementally build up a navigation map of the environment, while simultaneously using this map to update its estimated position.

Nevertheless, solving the Slam problem is not sufficient for guaranteeing an autonomous and safe navigation. The choice of the representation of the map is, of course, essential. The representation has to support the different levels of the navigation process: motion planning, motion execution and collision avoidance and, at the global level, the definition of an optimal strategy of displacement. The original formulation of the Slam problem is purely metric (since it basically consists in estimating the Cartesian situations of the robot and a set of landmarks), and it does not involve complex representations of the environment. However, it is now well recognized that **several complementary representations are needed to perform exploration, navigation, mapping, and control tasks successfully. We propose to use composite models of the environment that mix topological, metric, and grid-based representations.** Each type of representation is well adapted to a particular aspect of autonomous navigation: the metric model allows one to locate the robot precisely and plan Cartesian paths, the topological model captures the accessibility of different sites in the environment and allows a coarse localization, and finally the grid representation is useful to characterize the free space and design potential functions used for reactive obstacle avoidance. However, ensuring the consistency of these various representations during the robot exploration, and merging observations acquired from different viewpoints by several cooperative robots, are difficult problems. This is particularly true when different sensing modalities are involved. New studies to derive efficient algorithms for manipulating the hybrid representations (merging, updating, filtering...) while preserving their consistency are needed.

4. Application Domains

4.1. Application Domains

The natural applications of our research are obviously in robotics. 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 mostly interested in using visual servoing for aerial and space application, micromanipulation, autonomous vehicle navigation in large urban environments or for disabled or elderly people.

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, needle insertion, compensation of organ motion, 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 design 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.

5. New Software and Platforms

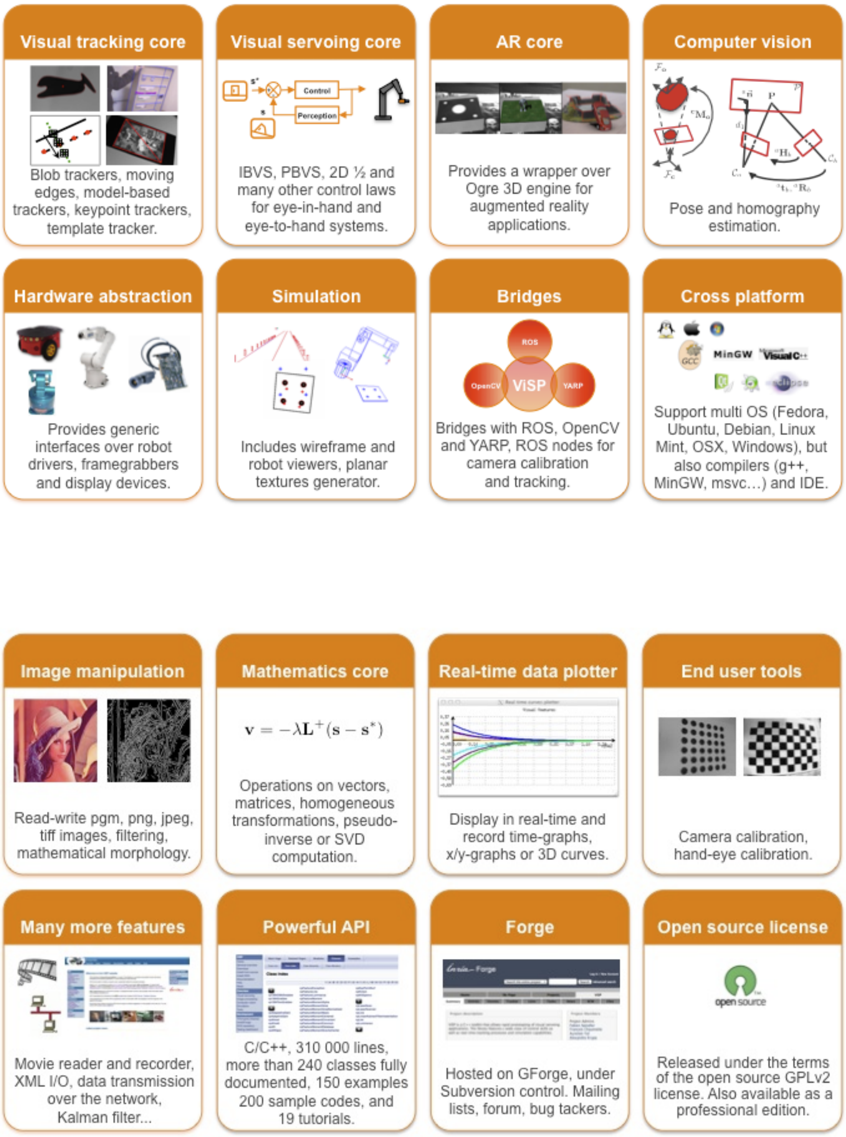
5.1. ViSP: a visual servoing and tracking software library

Participants: Fabien Spindler [correspondant], Aurélien Yol, Eric Marchand, François Chaumette.

Since 2005, we develop and release under the terms of the GPLv2 license, ViSP, an open source library available from http://team.inria.fr/lagadic/visp. It allows fast prototyping of visual tracking and visual servoing tasks. ViSP was designed to be independent with the hardware, to be simple to use, expandable and cross-platform.

ViSP allows to design 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. It involves a large set of elementary positioning tasks with respect to various visual features (points, segments, straight lines, circles, spheres, cylinders, image moments, pose...) that can be combined together, and image processing algorithms that allow tracking of visual cues (dots, segments, ellipses...), 3D model-based tracking of known objects or template tracking. Simulation capabilities are also available. ViSP and its full functionalities are presented in Fig. 1 and described in [5].

This year, we continued our efforts to improve the software by ensuring the compatibility with third-party libraries that evolves a lot like CMake 3.0.0 and OpenCV 3.0.0 and by enlarging the compatibility with exotic platforms like RaspberryPi. We also fixed some issues, allowed the model-based tracker to consider circles. We introduced new bar code and face detection but also tracking capabilities. Moreover, we completely re-factored the capabilities concerning keypoint detection and matching. We improved the documentation by providing new tutorials covering the main capabilities of the software. A new release was produced in February. The source code tarball was downloaded 1000 times. With the help of the community, this release was packaged for Debian and Ubuntu 14.04. A new release is in preparation.



Visual tracking core

Blob trackers, moving edges, model-based trackers, keypoint trackers, template tracker.

Visual servoing core

IBVS, PBVS, 2D ½ and many other control laws for eye-in-hand and eye-to-hand systems.

AR core

Provides a wrapper over Ogre 3D engine for augmented reality applications.

Computer vision

Pose and homography estimation.

Hardware abstraction

Provides generic interfaces over robot drivers, framegrabbers and display devices.

Simulation

Includes wireframe and robot viewers, planar textures generator.

Bridges

Bridges with ROS, OpenCV and YARP, ROS nodes for camera calibration and tracking.

Cross platform

Support multi OS (Fedora, Ubuntu, Debian, Linux Mint, OSX, Windows), but also compilers (g++, MinGW, msvc…) and IDE.

Image manipulation

Read-write pgm, png, jpeg, tiff images, filtering, mathematical morphology.

Mathematics core

$$\mathbf{v} = -\lambda \mathbf{L}^{+}(\mathbf{s} - \mathbf{s}^{*})$$

Operations on vectors, matrices, homogeneous transformations, pseudo-inverse or SVD computation.

Real-time data plotter

Display in real-time and record time-graphs, x/y-graphs or 3D curves.

End user tools

Camera calibration, hand-eye calibration.

Many more features

Movie reader and recorder, XML I/O, data transmission over the network, Kalman filter…

Powerful API

C/C++, 310 000 lines, more than 240 classes fully documented, 150 examples 200 sample codes, and 19 tutorials.

Forge

Hosted on GForge, under Subversion control. Mailing lists, forum, bug tackers.

Open source license

Released under the terms of the open source GPLv2 license. Also available as a professional edition.

Figure 1. This figure highlights ViSP main capabilities for visual tracking, visual servoing, and augmented reality that may benefit from computer vision algorithms. ViSP allows controlling specific platforms through hardware abstraction or in simulation. ViSP provides also bridges over other frameworks such as OpenCV and ROS. All these capabilities are cross-platform. Moreover, for easing the prototyping of applications, ViSP provides tools for image manipulation, mathematics, data plotting, camera calibration, and many other features. ViSP powerful API is fully documented and available on Inria's forge as an open source software under GPLv2 license.

Concerning ROS community, all the existing packages in "`vision_visp`" ROS stack (see http://wiki.ros.org/vision_visp) were updated and ported to indigo build system. To ease ViSP usage in the ROS framework, the last release was packaged for ROS.

ViSP is used in research labs in France, USA, Japan, Korea, India, China, Lebanon, Italy, Spain, Portugal, Hungary, Canada. For instance, it is used as a support in graduate courses at IFMA Clermont-Ferrand, University of Picardie in Amiens, Télécom Physique in Strasbourg and ESIR in Rennes.

5.2. DESlam software

Participant: Patrick Rives [correspondant].

The DESlam (Dense Egocentric Slam) software developed in collaboration with Andrew Comport from I3S in Sophia Antipolis was registered to the APP ("Agence de Protection des Programmes") (IDDN.FR.001.320001.000.S.P.2012.000.21000). This software proposes a full and self content solution to the dense Slam problem. Based on a generic RGB-D representation valid for various type of sensors (stereovision, multi-cameras, RGB-D sensors...), it provides a 3D textured representation of complex large indoor and outdoor environments and it allows localizing in real time (45Hz) a robot or a person carrying out a mobile camera.

5.3. HandiViz software

Participants: Marie Babel [correspondant], François Pasteau.

The HandiViz software proposes a semi-autonomous navigation framework of a wheelchair relying on visual servoing. It has been registered to the APP ("Agence de Protection des Programmes") as an INSA software (IDDN.FR.001.440021.000.S.P.2013.000.10000) and is under GPL license.

5.4. Platforms

5.4.1. Robot vision platforms

Participant: Fabien Spindler [correspondant].

We exploit two industrial robotic systems built by Afma Robots in the nineties to validate our researches in visual servoing and active vision. 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. 2). These robots are equipped with cameras. The Gantry robot allows also to embed grippers on its end-effector.

Seven papers published by Lagadic in 2014 enclose results validated on this platform [12], [18], [21], [24], [47], [51], [52].

5.4.2. Mobile robotics platforms

Participants: Fabien Spindler [correspondant], Erwan Demairy, Marie Babel, Patrick Rives.

5.4.2.1. Indoor mobile robots

For fast prototyping of algorithms in perception, control and autonomous navigation, the team uses Hannibal in Sophia Antipolis, a cart-like platform built by Neobotix (see Fig. 3.a), and, in Rennes, a Robotino from Festo (see Fig. 3.b) and Pioneer 3DX from Adept (see Fig. 3.c). These platforms are equipped with various sensors needed for Slam purposes, autonomous navigation and sensor-based control.

Moreover, to validate the researches in personally assisted living topic (see 6.2.1), we have in Rennes a six wheel electric wheelchair from Penny and Giles Drives Technology (see Fig. 3.d) and a five wheel electric wheelchair from You-Q (see Fig. 3.e). The control of the wheelchair is performed using a plug and play system between the joystick and the low level control of the wheelchair. Such a system lets us acquire the user intention through the joystick position and control the wheelchair by applying corrections to its motion. The wheelchairs have been fitted with cameras and eleven ultrasound sensors to perform the required servoing for assisting handicapped people.

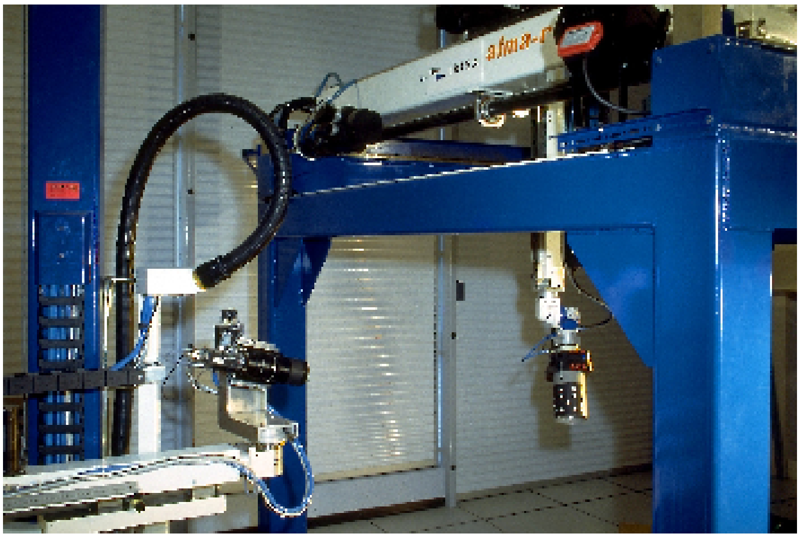


Figure 2. Lagadic robotics platforms for vision-based manipulation

Note that eleven papers exploiting the indoors mobile robots were published this year [16], [29], [30], [31], [33], [37], [43], [41], [42], [56], [58].

5.4.2.2. *Outdoor mobile robots*

The team exploits also Cycab urban electrical cars (see Figs. 3.f and 3.g). Two vehicles in Sophia Antipolis and one in Rennes are instrumented with cameras and range finders to validate researches in the domain of intelligent urban vehicle. Cycabs were used as experimental testbeds in several national projects.

Two papers published by Lagadic in 2014 enclose experimental results obtained with these outdoor mobile robots [11], [14].

5.4.2.3. *Technological Development Action (ADT) P2N*

The ADT P2N aims at sharing existing and in development codes between the Lagadic and E-Motion teams in the field of autonomous navigation of indoor robots. These codes are also used in the platforms involved in the large-scale initiative action PAL (Personnally Assisted Living, see Section 8.2.6).

This year, the most notable activities for this ADT have been to:

- make the Slam module developed by Lagadic usable by the E-Motion navigation module;
- port the code on the wheelchairs used in PAL;
- develop the core architecture running under ROS supporting the different sensors and platforms available in Sophia-Antipolis.
- demonstrate the social based navigation methods on the Hannibal platform (see Section 6.2.3)

5.4.3. *Medical robotics platforms*

Participants: Fabien Spindler [correspondant], Alexandre Krupa.

This testbed is of primary interest for researches and experiments concerning ultrasound visual servoing applied to probe positioning, soft tissue tracking or robotic needle insertion tasks described in Section 6.5.

This platform is composed by two Adept Viper six degrees of freedom arms (see Fig. 4.a). Ultrasound probes connected either to a SonoSite 180 Plus or an Ultrasonix SonixTouch imaging system can be mounted on a force torque sensor attached to each robot end-effector.

(a) (b) (c)

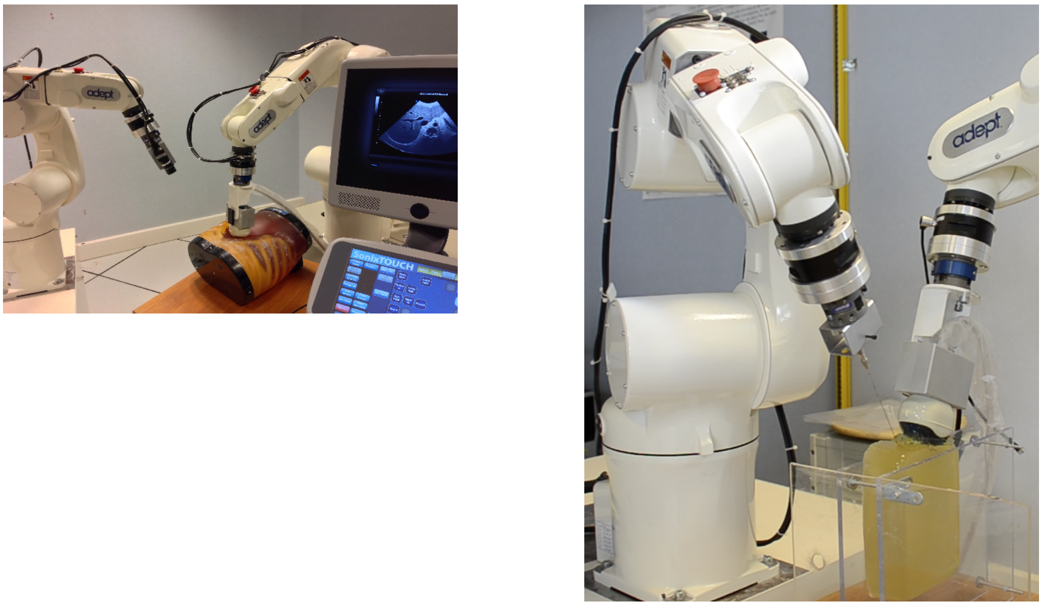
(d) (e)

(f) (g)

Figure 3. a) Hannibal platform, b) Robotino, c) Pioneer P3-DX robot, d) wheelchair from Penny and Giles Drives Technology, e) wheelchair from You-Q , f) Cycab available in Rennes, g) one of the Cycabs available in Sophia Antipolis.

We designed an experimental setup to test an autonomous robotic needle insertion method based on visual servoing 6.5.3. The experimental setup is composed with a gelatin phantom simulating soft tissues, a flexible biopsy needle actuated by an Adept Viper arm and a 3D ultrasound probe held by the second Adept Viper arm (see Fig. 4.b).

This year, six papers enclose experimental results obtained with this platform [13], [34], [35], [48], [49], [50].



(a) (b)

Figure 4. a) Lagadic medical robotics platforms. On the right Viper S850 robot arm equipped with a SonixTouch 3D ultrasound probe. On the left Viper S650 equipped with a tool changer that allows to attach a classical camera or biopsy needles. b) Robotic setup for autonomous needle insertion by visual servoing.

5.4.4. Humanoid robot

Participants: Giovanni Claudio, Fabien Spindler [correspondant].

Romeo is a humanoid robot from Aldebaran Robotics which is intended to be a genuine personal assistant and companion. In September, we were the first of the four European research laboratories that acquire a Romeo. For the moment only the upper part of the body (arms, head) is working. This research platform is now being used to validate our researches. We developed a first demonstration that make use of visual servoing and visual tracking approaches developed in the team to grasp a box and deliver it to a human (see Fig. 5).

5.4.5. Unmanned Aerial Vehicles (UAVs)

Participants: Fabrizio Schiano, Paolo Robuffo Giordano.

In 2014 the team also started some activities involving perception and control for single and multiple quadrotor UAVs, especially thanks to a grant from “Rennes Métropole” (see Section 8.1.4). To this end, we purchased two quadrotors from Mikrokopter Gmbh, Germany (Fig. 6.a), and one quadrotor from 3DRobotics, USA (Fig. 6.b). These quadrotors will be used as robotic platforms for testing a number of single and multiple flight control schemes with a special attention on the use of onboard vision as main sensory modality.

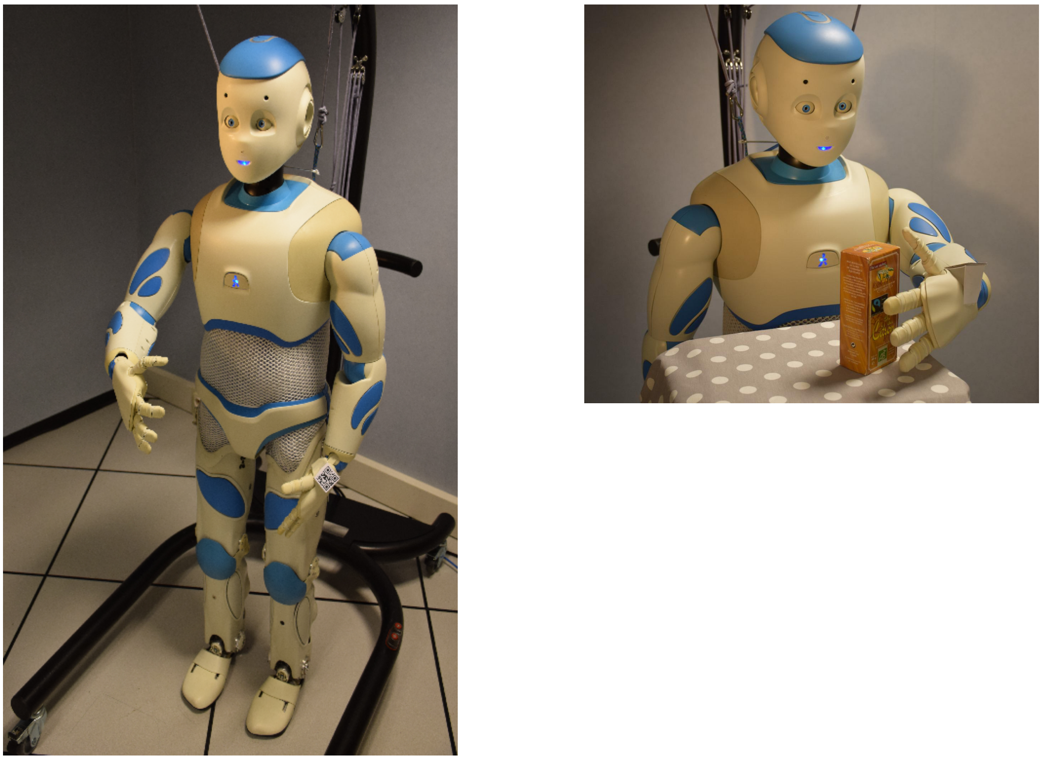


Figure 5. Romeo experimental platform.

(a) (b)

Figure 6. a) Quadrotor XL1 from Mikrokopter, b) Quadrotor Iris from 3DRobotics

6. New Results

6.1. Visual servoing

6.1.1. Photometric moment-based visual servoing

Participants: Manikandan Bakthavatchalam, François Chaumette.

The goal of this work is to determine an adequate set of visual features to control the six degrees of freedom of a dynamic system. Thanks to a collaboration with Omar Tahri from Le2I in Le Creusot, we have been able to improve the results obtained previously with shifted moments for increasing the stability domain of visual servoing [24].

6.1.2. Histogram-based visual servoing

Participants: Quentin Bateux, Eric Marchand.

Classically visual servoing considered the regulation in the image of a set of visual features (usually geometric features). Recently direct visual servoing schemes, such as photometric visual servoing, have been introduced in order to consider the image as a whole and thus avoid the extraction and the tracking of such geometric features. In this preliminary work, we propose a method to extend direct visual servoing approaches by using a global descriptor, namely intensity histograms, on the whole or multiple sub-sets of the images in order to achieve the control of a 6 degrees of freedom (DoF) robot.

6.1.3. Predictive visual servoing

Participants: Nicolas Cazy, Paolo Robuffo Giordano, François Chaumette.

This study is devoted to the application of predictive control to visual servoing. In a first step, we have developed and compared several predictive models that can be useful when some visual features leave the camera field of view or are lost because of occlusions [25].

6.1.4. Visual servoing of cable-driven parallel robot

Participant: François Chaumette.

This study is realized in collaboration with Rémy Ramadour and Jean-Pierre Merlet from Coprin group at Inria Sophia Antipolis. Its goal is to adapt visual servoing techniques for cable-driven parallel robot in order to achieve accurate manipulation tasks [46]. This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6).

6.1.5. Nanomanipulation

Participants: Le Cui, Eric Marchand.

We began a work, within the ANR P2N Nanorobust project (see Section 8.2.1), on the development of micro- and nano-manipulation within SEM (Scanning Electron Microscope). Our goal is to provide visual servoing techniques for positioning and manipulation tasks with a nanometer precision. This year, we focused on the characterisation of the projection model of a SEM along with the approach required for its calibration [26]. We then address the problem of 6 dof control using photometric feature under an optical microscope [27]. Finally, we focused on the definition of control law able to control the motion along the Z axes with a SEM microscope. Indeed, considering that a SEM is subject to parallel projection model, motion along this axis is not observable. We then address this problem using defocus information. An autofocus process has also been studied.

6.1.6. Audio-based control

Participants: Aly Magassouba, François Chaumette.

This study is not concerned with visual servoing, but to the application of the same principle of closed loop control schemes to audio sensors. It is made in collaboration with Nancy Bertin from Panama group at Inria Rennes-Bretagne Atlantique. In a first step, we have determined the analytical form of the interaction matrix of audio features based on the time difference of arrival on two microphones. From this modeling step, we have determined the different virtual linkages that can be realized in function of the number and configuration of sources.

6.2. Visual navigation of mobile robots

6.2.1. Automous navigation of wheelchairs

Participants: Vishnu Karakkat Narayanan, François Pasteau, Marie Babel, François Chaumette.

The goal of this work is to design an autonomous navigation framework of a wheelchair by means of a single camera and visual servoing. We first focused on a corridor following task where no prior knowledge of the environment is required. The servoing process matches the non-holonomic constraints of the wheelchair and relies on two visual features, namely the vanishing point location and the orientation of the median line formed by the straight lines related to the bottom of the walls. This overcomes the initialization issue typically raised in the literature [9]. The control scheme has been implemented onto a robotized wheelchair and results show that it can follow a corridor with an accuracy of ±3 cm [16].

We then focused on a door passing task [33]. This doorway passing (and corridor turning) task employs the position of a single doorpost in the image as an input to a Lyapunov-based control scheme which allows the wheelchair to take up a desired trajectory about the doorpost. This trajectory avoids collision with the wall and guarantees that the wheelchair positions itself in front of the doorway regardless of its initial position. Results in simulation demonstrate the convergence and robustness of both control schemes. Experiments conducted on a wheelchair indicate the validity of applying the proposed low-level control system [16].

This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6) as well as of the Apash project (see Section 8.1.1).

6.2.2. Semi-autonomous control of a wheelchair for navigation assistance along corridors

Participants: Vishnu Karakkat Narayanan, Marie Babel, François Pasteau, Alexandre Krupa.

This study concerns a semi-autonomous control approach that we designed for safe wheelchair navigation. The control relies on the combination of primary tasks of wall avoidance as well as door passing performed by a dedicated visual servoing framework and a manual steering task. A smooth transition from manual driving to assisted navigation is obtained thanks to a gradual visual servoing activation method that guarantees the continuity of the control law. The visual servoing task is then progressively activated, when the wheelchair gets closer to the walls or doorposts, in order to avoid collisions [43]. Experimental results clearly show the ability of the approach to provide an efficient solution for wall avoiding and doorway passing purposes [58]. This study is in the scope of the Inria large-scale initiative action PAL (see Section 8.2.6) as well as of the Apash project (see Section 8.1.1). Tests with disabled patients in the rehabilitation center Pôle Saint Hélier (Rennes) are under progress and first results prove the ability of our system to smoothly correct the trajectory of the wheelchair in case of hazardous situations.

Current research works are oriented towards multimodal sensor-based servoing, as well as haptic feedback that leads to an intuitive assistive wheelchair navigation. This work is realized in collaboration with Maud Marchal (Hybrid team). In addition, we are currently working with e-Motion team to design a vision-based human-aware semi-autonomous navigation system.

6.2.3. Social Spacing and human-robot interaction

Participants: Panagiotis Papadakis, Patrick Rives.

A novel probabilistic framework was introduced capable of instantiating diverse models of social spacing and accounting for distinctive dimensions in human-robot interaction, namely, perception capacity and certainty [42]. We have concretely shown how our method allows smooth adaptation in the situation awareness of a robot within common human-robot interaction examples and further showed its utility at the level of path planning by adapting trajectories to social sensitivity levels.

This approach is currently extended to take into account human activity cues in order to enhance robot mapping and navigation and in particular in filtering noisy human detections, detecting passages such as doors and staircases, inferring space occupancy and allowing navigation within unexplored areas.

6.2.4. Target tracking

Participants: Ivan Markovic, François Chaumette.

This study was realized in the scope of the FP7 Regpot Across project (see Section 8.3.1.2) during the three-month visit of Ivan Markovic, Ph.D. student at the University of Zagreb. It consisted in developing a pedestrian visual tracking from an omni-directional fish-eye camera and a visual servoing control scheme so that a mobile robot is able to follow the pedestrian [37]. This study has been validated on our Pioneer robot (see Section 5.4.2).

6.2.5. Obstacle avoidance

Participants: Suman Raj Bista, Fabien Spindler, François Chaumette.

This study was realized in collaboration with Andrea Cherubini who is now Assistant Prof. at Université de Montpellier. It is concerned with our long term researches about visual navigation from a visual memory without any accurate 3D localization [4]. In order to deal with obstacle avoidance while preserving the visibility in the visual memory, we have proposed a control scheme based on tentacles for fusing the data provided by a pan-tilt camera and a laser range sensor [11]. A new study devoted to indoors navigation from segments has started recently.

6.3. Visual tracking and state estimation

6.3.1. 3D model-based tracking

Participant: Eric Marchand.

This study focused on the issue of estimating the complete 3D pose of the camera with respect to a potentially textureless object, through model-based tracking. We proposed to robustly combine complementary geometrical and color edge-based features in the minimization process, and to integrate a multiple-hypotheses framework in the geometrical edge-based registration phase [45]. This method will be tested in the scope of the FP7 RemoveDebris project [36].

6.3.2. Pose estimation through plane tracking

Participants: Aurélien Yol, Eric Marchand.

We proposed a method for localizing an Unmanned Aerial Vehicle (UAV) using georeferenced aerial images. Here we provide a multiple usage localization algorithm based on vision only. To ensure robustness, we choose to use the Mutual Information (MI) within a dense tracking process. MI proved to be very robust toward local and global scene variations. However, dense approaches are often related to drift disadvantages. We solve this problem by using georeferenced images. The localization algorithm has been demonstrated through the localization of a hexarotor UAV fitted with a downward looking camera during real flight tests [53].

6.3.3. 3D tracking of deformable objects

Participants: Bertrand Delabarre, Eric Marchand.

We consider the problem of dense non-rigid visual tracking robust towards global illumination perturbations of the observed scene. The similarity function is based on the sum of conditional variance (SCV). With respect to most approaches that minimize the sum of squared differences, which is poorly robust towards illumination variations in the scene, the choice of SCV as our registration function allows the approach to be naturally robust towards global perturbations. Moreover, a thin-plate spline warping function is considered in order to take into account deformations of the observed template [28].

6.3.4. Structure from motion

Participants: Riccardo Spica, Paolo Robuffo Giordano, François Chaumette.

Structure from motion (SfM) is a classical and well-studied problem in computer and robot vision, and many solutions have been proposed to treat it as a recursive filtering/estimation task. However, the issue of *actively* optimizing the transient response of the SfM estimation error has not received a comparable attention. In the work [18], we showed how to design an online active SfM scheme characterized by an error transient response equivalent to that of a reference linear second-order system with desired poles. Indeed, in a nonlinear context, the observability properties of the states under consideration are not (in general) time-invariant but may depend on the current state and on the current inputs applied to the system. It is then possible to simultaneously act on the estimation gains and system inputs (i.e., the camera velocity for SfM) in order to optimize the observation process and impose a desired transient response to the estimation error. The theory has a general validity and can be applied to many different contexts such as when dealing with point features [18], solid objects like spheres or cylinders [51], or planar regions [47]. Furthermore, the active SfM scheme can also be embedded within a classical visual servoing law exploiting the redundancy of the camera motion w.r.t. the considered visual task [52].

6.3.5. Robust visual odometry

Participants: Tawsif Gokhool, Patrick Rives, Renato José Martins.

Our aim is concentrated around building ego-centric topometric maps represented as a graph of salient keyframe nodes [14]. Additionally, visual odometry from frame to keyframe alignment helps significantly in drift reduction. On the other hand, the sparsity in this kind of graphical representation leads to reduced overlapping between keyframes which can degrade localisation robustness. Our chosen spherical 360^0 field of view (FOV) configuration alleviates the overlapping issue by providing an enriched model of the environment with photometric and geometric information content. Following a multitude of advantages with information fusion, merging of frames in a single representation deals with the problem of data redundancy and sensor noise suppression.

Therefore, the second fold of this work consisted in improving the identified conceptual loopholes above by first proposing a generic uncertainty propagation model as applied to our spherical RGB-D database. Secondly, a probabilistic framework was derived which led to a Mahalanobis inconsistency test incorporating both geometric and photometric uncertainty models [32]. Our framework was further improved by adding up a probabilistic model to filter out dynamic points temporally. Finally, the entire probabilistic framework was applied in order to track the most stable points over time.

6.4. 3D Scene Mapping

6.4.1. New RGB-D sensor design for indoor 3D mapping

Participants: Eduardo Fernandez Moral, Patrick Rives.

A multi-sensor device has been developed for omnidirectional RGB-D (color+depth) image acquisition (see Fig. 3.a). This device allows to acquire such omnidirectional images at high frame rates (30 Hz). This approach has advantages over other alternatives used today in terms of accuracy and real-time spherical image construction for indoor environments, which are specially interesting for mobile robotics. This device has important prospective applications as fast 3D-reconstruction or Slam.

A calibration method for such device was developed [31], which takes into account the bias of each sensor independently. The proposed calibration method does not require any specific calibration pattern, taking into account the planar structure from the scene to cope with the fact that there is no overlapping between sensors.

In a first instance, this sensor has been exploited for localization and mapping research with mobile robots. For that, the sensor is mounted on a mobile platform together with an standard computer (see Fig. 3.a). A method to perform image registration and visual odometry has been developed. This method relies in the matching of planar primitives that can be efficiently obtained from the depth images. This technique performs considerably faster than previous registration approaches like ICP, or dense photoconsistency alignment. These last achieve however a better accuracy than our method, what suggests that our method can be used as an initial step to speed-up those.

Slam is also addressed with this device. A solution to this problem using our omnidirectional RGB-D sensor is being researched. The ongoing experiments have shown some initial results for metric-topological pose-graph Slam, where the map consists of a set of spherical keyframes, which are located in a topological arrangement according to their shared observations.

6.4.2. Compact 3D scene representation

Participants: Renato José Martins, Patrick Rives, Tawsif Gokhool.

This work follows in the direction of precise and compact scene representation of large scale environments. The aim is to build a complete geometric and photometric “minimal” model, which is stored within a sparse set of augmented spherical images to asset photo-geometry consistence of the scene from multiple points-of-views. In this direction, an uncertainty model from the full structure combined with those of poses was proposed for point-to-point egocentric fusion. This model allows to reduce sensor noise in a particular keyframe sphere when performing a multi-frame fusion scheme of coherent near information. This first fusion scheme is then improved by exploiting the rigidity/influence of neighboring points representing the surface. For that, an intermediary higher level abstraction of the point cloud is generated by partitioning the input domain into elementary cells, then reducing the number of degrees of freedom and enforcing constraints over the points segmented as being part of the same surface.

The adopted solution is a “weaker” representation of a 3D boundary mesh, based on discontinuous convex planar patches, with the segmentation being done considering the geometry (region growing) or photometry (SLIC superpixels). This synthetic scene built with the planar geometric police proved to well represent the original scene (for both indoor and outdoor real data) with a significant small amount of patches and it is exploited to build robust useful “dynamic” 4D world model, which in turn can be used for assisted/autonomous navigation or virtual reality applications.

6.4.3. Semantic mapping

Participants: Romain Drouilly, Patrick Rives, Panagiotis Papadakis.

Autonomous navigation is one of the most challenging problems to address to allow robots to evolve in our everyday environments. Map-based navigation has been studied for a long time and researches have produced a great variety of approaches to model the world. However, semantic information has only recently been taken into account in those models to improve robot efficiency [56]. The goal of this work is to study how semantics can be used to improve all the steps of navigation process. In a first time, we have developed a new navigation-oriented hybrid metric-topological-semantic model of the world. It captures high-level information and uses it to build extremely compact description of large environments. Then we have used it to design an efficient localization algorithm, able to find a given map content faster than classical methods and allowing human-understandable queries [30]. In a second time, we have studied how semantics can be used to discover unobserved things in the scene. Particularly, we have shown that both statics and dynamic entities, identified by a robot, can inform about the structure of the environment in unobserved areas [29] . We have used this to do “map extrapolation”, that is extending a map beyond robot’s perceptual limits by reasoning on semantics. This approach has been shown to be of great interest in everyday-life environment. Finally, we have proposed a new scheme for trajectory planing, taking into account not only geometric constraints but also high-level understanding of the world. We have shown the usefulness of this approach to navigate complex environments with highly dynamic areas on both simulated and real-world datasets, well-suited for large outdoor environment navigation.

6.4.4. Augmented reality

Participant: Eric Marchand.

Using Slam methods becomes more and more common in Augmented Reality (AR). To achieve real-time requirement and to cope with scale factor and the lack of absolute positioning issue, we proposed to decouple the localization and the mapping step. This approach has been validated on an Android Smartphone through a collaboration with Orange Labs [38][39]

6.5. Medical robotics

6.5.1. Non-rigid target tracking in ultrasound images based on hierarchical grid interpolation

Participants: Lucas Royer, Jason Chevrie, Marie Babel, Alexandre Krupa.

In order to track the motion of a tumour or cyst during needle insertion, we developed a first approach to track a deformable target within a sequence of 2D ultrasound images. It is based on a dedicated hierarchical grid interpolation algorithm (HGI) that is typically used for real-time video compression purposes. This approach provides a continuous motion representation of the target by using a grid of control points that models both their global displacement and local deformations. The motion of each control point is estimated by a hierarchical and multi-resolution local search method in order to minimize the sum of squared difference of the target pixel intensity between successive images. This approach was validated from 2D ultrasound images of real human tissues undergoing rigid and non-rigid deformations [48] and was recently adapted for tracking 3D deformations.

6.5.2. Non-rigid target tracking in ultrasound images based on physically-based model

Participants: Lucas Royer, Alexandre Krupa.

A second approach for automatically tracking deformable target within 2D ultrasound images has been developed [50]. It combines dense information with a physically-based model and has therefore the advantage of not using any fiducial marker. The physical model is represented by a mass-spring damper system driven by external and internal forces. The external forces are obtained by maximizing an image similarity metric between a reference target and the deformed target along the time. The internal forces of the mass-spring damper system constrain the deformation to be physically plausible and therefore efficiently reduce the sensitivity to the speckle noise. This second approach was validated on simulated and real data, both for rigid and non-rigid motions of soft tissues [49]. It was recently extended for deformable target tracking in 3D ultrasound volumes.

6.5.3. 3D steering of flexible needle by visual servoing

Participants: Alexandre Krupa, Pierre Chatelain.

The objective of this work is to provide robotic assistance during needle insertion procedures such as biopsy or ablation of localized tumor. A method has been developed for steering a beveled-tip flexible needle actuated by a robotic arm in such a way to control the needle curvature in 3D space [34]. It is based on the design of a new duty-cycling control strategy that makes possible to control both the 2 lateral angular velocities and the insertion velocity of the needle tip (3 DOF). An image-based visual servoing approach has then been developed to automatically position the needle tip on a 3D target indicated by the user. It is based on the use of geometrical visual features extracted from 2 images provided by 2 orthogonal cameras observing a translucent gelatin phantom where the needle is inserted. Preliminary results of this automatic targeting task demonstrate the feasibility of this new concept and its robustness to needle kinematic model errors [35]. We recently extended this approach to automatically steer the needle toward a target by an image-based visual servoing that uses geometrical features extracted from images provided by a 3D ultrasound probe.

6.5.4. Optimization of ultrasound image quality by visual servoing

Participants: Pierre Chatelain, Alexandre Krupa.

This study focuses on the automatic positioning of a 2D ultrasound probe in such a way to optimize the quality of the acquired ultrasound images. It is based on the recent framework of ultrasound confidence map, developed in the Chair for Computer Aided Medical Procedures and Augmented Reality of Prof. Nassir Navab, which aims at estimating the per-pixel quality of the ultrasound signal based on a model of sound propagation in soft tissues. In collaboration with Nassir Navab we considered this ultrasound confidence map as a new modality and recently designed a visual servoing control law for image quality optimization.

6.6. Control of single and multiple Unmanned Aerial Vehicles

6.6.1. State estimation and flight control of quadrotor UAVs

Participant: Paolo Robuffo Giordano.

Over the last years the robotics community witnessed an increasing interest in the Unmanned Aerial Vehicle (UAV) field. In particular quadrotor UAVs have become more and more widespread in the community as experimental platform for, e.g., testing novel 3D planning, control and estimation schemes in real-world indoor and outdoor conditions. Indeed, in addition to being able to take-off and land vertically, quadrotors can reach high angular accelerations thanks to the relatively long lever arm between opposing motors. This makes them more agile than most standard helicopters or similar rotorcraft UAVs, and thus very suitable to realize complex tasks such as aerial mapping, air pollution monitoring, traffic management, inspection of damaged buildings and dangerous sites, as well as agricultural applications such as pesticide spraying.

Despite these clear advantages, a clear shortcoming of the quadrotor design lies in its inherent underactuation (only 4 actuated propellers for the 6 dofs of the quadrotor pose). This underactuation limits the quadrotor flying ability in free or cluttered space and, furthermore, it also degrades the possibility of interacting with the environment by exerting desired forces in arbitrary directions. In [17], a novel design for a quadrotor UAV with tilting propellers which is able to overcome these limitations has been presented and experimentally validated. Indeed, the additional set of 4 control inputs actuating the propeller tilting angles can be shown to yield full actuation to the quadrotor position/orientation in space, thus allowing it to behave as a fully-actuated flying vehicle and to overcome the aforementioned underactuation problem.

This work has been realized in collaboration with the Max Planck Institute for Biological Cybernetics, Tübingen, Germany.

6.6.2. Collective control of multiple UAVs

Participant: Paolo Robuffo Giordano.

The challenge of coordinating the actions of multiple robots is inspired by the idea that proper coordination of many simple robots can lead to the fulfilment of arbitrarily complex tasks in a robust (to single robot failures) and highly flexible way. Teams of multi-robots can take advantage of their number to perform, for example, complex manipulation and assembly tasks, or to obtain rich spatial awareness by suitably distributing themselves in the environment. Within the scope of robotics, autonomous search and rescue, firefighting, exploration and intervention in dangerous or inaccessible areas are the most promising applications.

In the context of multi-robot (and multi-UAV) coordinated control, *connectivity* of the underlying graph is perhaps the most fundamental requirement in order to allow a group of robots accomplishing common goals by means of *decentralized* solutions. In fact, graph connectivity ensures the needed continuity in the data flow among all the robots in the group which, over time, makes it possible to share and distribute the needed information. However, connectivity alone is not sufficient to perform certain tasks when only *relative sensing* is used. For these systems, the concept of *rigidity* provides the correct framework for defining an appropriate sensing and communication topology architecture. Rigidity is a combinatorial theory for characterizing the “stiffness” or “flexibility” of structures formed by rigid bodies connected by flexible linkages or hinges. In a broader context, rigidity turns out to be an important architectural property of many multi-agent systems when a common inertial reference frame is unavailable. Applications that rely on sensor fusion for localization, exploration, mapping and cooperative tracking of a target, all can benefit from notions in rigidity theory. The concept of rigidity, therefore, provides the theoretical foundation for approaching decentralized solutions to the aforementioned problems using distance measurement sensors, and thus establishing an appropriate framework for relating system level architectural requirements to the sensing and communication capabilities of the system.

In [22], a decentralized gradient-based rigidity maintenance action for a group of quadrotor UAVs has been proposed and tested in real experimental conditions. By starting in a rigid configuration, the group of UAVs is able to estimate their relative position from sole relative distance measurements, and then use these estimated relative positions in a control action able to preserve rigidity of the whole formation despite presence of sensor limitations (maximum range and line-of-sight occlusions), possible collisions with obstacles and inter-robot collisions. Furthermore, in [54] the rigidity theory has been extended to the case of *bearing measurements*, and directed graphs.

These works were realized in collaboration with the robotics group at the Max Planck Institute for Biological Cybernetics, Tübingen, Germany and with Technion, Israel.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Robocortex

Participants: Souriya Trinh, Fabien Spindler, François Chaumette.

no. Inria Rennes 8492, duration: 13 months.

This contract with the Inria spin off company Robocortex started in March 2014. It is devoted to the visual tracking and 3D localization of some particular targets.

7.2. Bilateral Grants with Industry

7.2.1. Astrium EADS

Participants: Tawsif Gokhool, Patrick Rives.

no. Inria Sophia 7128, duration: 36 months.

The objective of this project that started in February 2012 is to investigate the general problem of visual mapping of complex 3D environments that evolve over time. This contract supports Tawsif Gokhool's Ph.D. (see Section 6.3.5).

7.2.2. ECA Robotics

Participants: Romain Drouilly, Patrick Rives.

no. Inria Sophia 7030, duration: 36 months.

This project started in May 2012. It aims at specifying a semantic representation well adapted to the problem of navigation in structured environment (indoors or outdoors). This contract is devoted to support the Cifre Convention between ECA Robotics and Inria Sophia Antipolis regarding Romain Drouilly's Ph.D.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Oseo Apash project

Participants: François Pasteau, Marie Babel.

no Insa Rennes 2012-230, duration: 24 months.

Started in September 2012 and finished in July 2014, the Apash project was supported by the Images & Réseaux cluster. It involved three laboratories connected to INSA Rennes, namely Irisa/Inria, IETR and LGCGM. One industrial partner took part into this project: Ergovie. This project aimed at designing a driving assistance for electrical wheelchair towards the autonomy and security of disabled people. The work realized within this project is described in Section 6.2.1.

8.1.2. HandiViz project - SATT Ouest Valorisation

Participants: François Pasteau, Marie Babel.

duration: 12 months.

This project strated in June 2014. Thanks to a strong collaboration with Ergovie Company and the rehabilitation center Pôle Saint Hélier (Rennes), the semi-autonomous navigation solution designed for wheelchair systems (see Section 6.2.1) has been medically validated and tested by patients. The resulting technology is currently under transfer towards Ergovie (SATT/INSA funding). This technology, compliant with any off-the-shelf electrical wheelchair, is expected to be commercialized at mid 2015. We expect that this technology should be helpfull for many handicapped people. In particular, clinical trials have shown that such a system can lift the medical interdiction to drive wheelchairs for people who suffer from severe handicap such as hemispatial neglect or cerebral palsy.

8.1.3. ARED NavRob

Participants: Suman Raj Bista, Paolo Robuffo Giordano, François Chaumette.

no Inria Rennes 8033, duration: 36 months.

This project funded by the Brittany council started in October 2013. It supports in part Suman Raj Bista's Ph.D. about visual navigation of a humanoid robot (see Section 8.2.4).

8.1.4. "Equipement mi-lourd Rennes Metropoles"

Participant: Paolo Robuffo Giordano.

no Irisa CNRS Rennes 14C0481, duration: 36 months.

A grant from "Rennes Métropole" has been obtained in June 2014 and will support the activities related to the use of drones (quadrotor UAVs). The platform described in Section 5.4.5 has been purchased thanks to this grant.

8.2. National Initiatives

8.2.1. ANR P2N Nanorobust

Participants: Le Cui, Eric Marchand.

no. UR1 11FA310-06D, duration: 48 months.

This project started in November 2011. It is composed of a consortium managed by Femto-ST in Besançon with LPN and Isir in Paris, Thalès and Lagadic group through the "Université de Rennes 1". Nanorobust deals with the development of micro- and nano-manipulation within SEM (Scanning Electron Microscope). Our goal is to provide visual servoing techniques for positioning and manipulation tasks with a nanometer precision.

8.2.2. ANR Contint Visioland

Participants: Noël Mériaux, Patrick Rives, François Chaumette.

duration: 48 months.

This project started in November 2013. It is composed of a consortium managed by Onera in Toulouse with Airbus, Spikenet Technology, IRCCyN, and Lagadic. Its aim is to develop vision-based localization and navigation techniques for autonomous landing on a runway.

8.2.3. PEA Decsa

Participants: Aurélien Yol, Eric Marchand.

no Inria Rennes 6630, duration: 36 months.

This project started in November 2011. It is composed of a consortium managed by Astrium/Airbus with the Novadem, Sirehna, Spot Image and Magellium companies, and with the Inria Lagadic and Steep groups (Peter Sturm). It is devoted to the development of navigation and perception algorithms for small drones in urban environment.

8.2.4. Oseo Romeo 2

Participants: Nicolas Cazy, Suman Raj Bista, Fabien Spindler, Paolo Robuffo Giordano, François Chaumette.

no Inria Rennes 7114, duration: 48 months.

This project started in November 2012. It is composed of a large consortium managed by Aldebaran Robotics. It aims to develop advanced control and perception functionalities to a humanoid robot. It supports in part Suman Raj Bista's Ph.D. about visual navigation of a humanoid robot, as well as Nicolas Cazy's Ph.D. about model-based predictive control for visual servoing.

8.2.5. Equipex Robotex

Participants: Fabien Spindler, François Chaumette.

no Inria Rennes 6388, duration: 10 years.

Lagadic is one of the 15 French partners involved in the Equipex Robotex network. It is devoted to get significative equipments in the main robotics labs in France. In a near future, we plan to buy a humanoid robot, Romeo, by Aldebaran Robotics.

8.2.6. Inria large scale initiative action PAL

Participants: Panagiotis Papadakis, François Pasteau, Vishnu Karakkat Narayanan, Erwan Demairy, Marie Babel, Patrick Rives, François Chaumette.

Lagadic participates in the large-scale initiative action PAL (Personally Assisted Living) to develop technologies and services to improve the autonomy and quality of life for elderly and fragile persons. PAL started in September 2009 for 5 years. The purpose of PAL is to provide an experimental infrastructure, in order to facilitate the development of models, tools, technologies and concept demonstrations. Using the skills and objectives of the involved teams, four research themes have been defined: a) assessing the degree of frailty of the elderly, b) mobility of people, c) rehabilitation, transfer and assistance in walking, and d) social interaction. Lagadic is currently involved in the themes "mobility of people" and "assistance in walking" through collaborations with the EPI e-Motion (Grenoble), EPI Coprin (Sophia-Antipolis), and Handibio (Toulon). See Sections 6.2.1, 6.2.2 and 6.1.4, as well as [55].

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. FP7 Space RemoveDEBRIS

Participants: Eric Marchand, Fabien Spindler, François Chaumette.

Instrument: Specific Targeted Research Project

Duration: from October 2013 till September 2016

Coordinator: University of Surrey (United Kingdom)

Partner: Surrey Satellite Technology (United Kingdom), Astrium (Toulouse, France and Bremen, Germany), Isis (Delft, The Netherlands), CSEM (Neuchâtel, Switzerland), Stellenbosch University (South Africa).

Inria contact: François Chaumette

Abstract: The goal of this project is to validate the model-based tracking algorithms developped during Antoine Petit's Ph.D. (see Section 6.3.1) on images acquired during an actual space debris removal mission.

8.3.1.2. FP7 Regpot Across

Participant: François Chaumette.

Program: Regpot

Project acronym: Across

Project title: Center of Research Excellence for Advanced Cooperative Systems

Duration: from September 2011 till March 2015

Coordinator: Prof. Ivan Petrovic from University of Zagreb (Croatia)

Other partners: KTH (Sweden), ETHZ (Switzerland), TUM (Germany), University of Manchester (UK), Vienna University of Technology (Austria), Politecnico di Milano (Italy), University of Sevilla (Spain), Eindhoven University of Technology (The Netherlands), University of Athens (Greece), etc.

Abstract: the goal of this project is to enhance collaborations with the University of Zagreb.

8.4. International Initiatives

8.4.1. Inria Associate Teams

Participant: Marie Babel.

Sampen (Self Adaptive Mobile Perception and Navigation) is an Inria associated team with the Iceira Lab supervised by Prof Ren C. Luo at the National University of Taiwan. It has been accepted in 2014 for 2 years. The coordinator of the team for Inria is Anne Spalanzani from UPMF University at Grenoble. The other French participants are Marie Babel, Daney David (Phoenix group in Bordeaux) and Christian Laugier (e-Motion group in Grenoble).

The aim of the project is to propose a self-adaptive system of perception combined with a system of autonomous navigation. Usually, systems of perception rely on a set of specific sensors and a calibration is done in a specific environment. We propose to develop some methods to make perception systems adaptive to the environmental context and to the set of sensors used. This perception, that can be embedded on the mobile robot as well as on home structures (wall, ceiling, floor), will be helpful to localize agents (people, robot) present in the scene. Moreover, it will give information to better understand social scenes.

8.4.1.1. Informal International Partners

- As a follow up to the long term collaboration with the "Centro de Tecnologia da Informação Renato Archer" (CTI) in Campinas (Brazil), a new Ph.D. student, Renato José Martins, joined the team in Sophia Antipolis thanks to a grant from the CNPq (2013-2017). He is co-directed by Patrick Rives and Samuel Siqueira Bueno from "Divisão de Robótica e Visão Computacional" at CTI.
- Alexandre Krupa has a collaboration with Nassir Navab from the Technische Universität München concerning the joint supervision of Pierre Chatelain's Ph.D.
- Patrick Rives has a collaboration with Javier Gonzales-Jimenez from the University of Malaga (Spain). Eduardo Fernandez-Moral who received his PhD in Malaga by September 2014, is currently on a Postdoctoral position in Sophia Antipolis.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

- Hideaki Uchiyama, associate professor at Kyushu University, Japan, visited the group in Rennes for 3 weeks in December 2014 to work on augmented reality.
- Ivan Markovic, postdoctoral researcher at the University of Zagreb, spent a three-month visit in Rennes in the scope of the FP7 Regpot Across project (see Section 8.3.1.2 and 6.2.4).

8.5.2. Visits to International Teams

- Pierre Chatelain spent 2 one-week visits in Nassir Navab's lab at TUM, Germany, in the scope of his Ph.D.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. general chair, scientific chair

- Paolo Robuffo Giordano co-organized the Workshop "On the centrality of decentralization in multi-robot systems: holy grail or false idol?" at ICRA 2014, Hong Kong, China

9.1.1.2. member of the organizing committee

- Paolo Robuffo Giordano co-organized the 7-th International Workshop on Human-Friendly Robotics, Pontedera, Italy

9.1.2. Scientific events selection

9.1.2.1. member of the conference program committee

- François Chaumette: ICRA'14, ICRA'15
- Eric Marchand: ICRA'14, RFIA'14 (area chair), ICIP'14
- Patrick Rives: RFIA'14
- Paolo Robuffo Giordano: RSS'14, ICRA'14, DARS'14, RSS'15
- Marie Babel: ICIP'14, ICRA'15

9.1.2.2. reviewer

- François Chaumette: ICRA'14, RSS'14, IROS'14, , WAFR'14, ICRA'15
- Eric Marchand: ICRA'14, ICIP'14, IROS'14, ICRA'15
- Patrick Rives: ICRA'15, IROS'14, MVIGRO'14, RFIA'14, ECCV'14, ASROB'14
- Paolo Robuffo Giordano: ICRA'14, IROS'14, MSC'14, IFAC WC'14, ICRA'15
- Alexandre Krupa: ICRA'14, IROS'14, IPCAI'14, ICRA'15, ISBI'15

9.1.3. Journal

9.1.3.1. member of the editorial board

- Eric Marchand and Paolo Robuffo Giordano are Associate Editors of the IEEE Trans. on Robotics.
- Eric Marchand is a Guest Editor (with Peter Corke and Jana Kosecka) of a Special Issue of the Int. Journal of Robotics Research on Robot Vision.
- François Chaumette is in the Editorial Board of the Int. Journal of Robotics Research.

9.1.3.2. reviewer

- François Chaumette: IEEE Trans. on Robotics (7), Int. Journal of Robotics Research (1), IEEE Trans. on Automatic Control (1), Robotics and Autonomous Systems (1)

- Eric Marchand: IEEE Trans. on Robotics (8), Int. Journal of Robotics Research (4), Autonomous Robots (1)
- Patrick Rives: Int. Journal of Robotics Research (1), Journal of Control (1)
- Paolo Robuffo Giordano: IJRR (2), T-CST (2), JHRI (1), TAC (1), TRO (1)
- Alexandre Krupa: Robotics and Autonomous Systems (1)

9.1.4. Selection committees

- François Chaumette was in the selection committee for an Assistant Professor position at the "Université Picardie-Jules Verne" in Amiens. He also served in the jury for the selection of research scientists (SRP/ARP) at Inria.
- Marie Babel was in the selection committee for research scientists (CR2) at Inria Rennes-Bretagne Atlantique. She also served in the selection committee for an Assistant Professor position in robotics at the "Université de Lorraine".
- Paolo Robuffo Giordano and François Chaumette were in the selection committee for an Assistant Professor position in robotics at the "Université de Rennes 1".
- Eric Marchand was in the selection committee for a Professor position in image processing at Insa in Rennes.
- Patrick Rives as a member of the Inria evaluation committee was in the selection committee for research scientists (CR2) at Inria Nancy-Grand Est and Inria Bordeaux-Sud-Ouest, and also in the selection committees for senior research scientists (DR2, DR1, and DR0).

9.1.5. Participation in seminars, invitation

- François Chaumette and Paolo Robuffo Giordano were invited to give a talk during the final workshop of the FP7 Regpot project at Dubrovnik, Croatia, in September 2014.
- Alexandre Krupa was invited to give a talk in the tutorial session on Mechatronics for medical robotics at the IEEE/ASME Conf. on Advanced Intelligent Mechatronics, Besançon, France, July 2014 [59].

9.1.6. Animation at the international level

- François Chaumette served in the 2014 IEEE RAS Fellow Nomination Committee and in the 2014 IEEE RAS Chapter of the year Award Committee. He was also a member of the jury in charge of the 2014 IEEE ICRA Best Vision paper award.
- Paolo Robuffo Giordano served as External Reviewer for the EU FP7 Project "SHERPA"

9.1.7. Animation at the national level

- François Chaumette and Patrick Rives are members of the scientific council of the "GdR Robotique" and JNRR. They have both served in the jury to select the best French Ph.D. thesis in robotics.
- Patrick Rives is a member of the Inria evaluation committee.
- Eric Marchand is in the board of the "Association Française pour la Reconnaissance et l'Interprétation des Formes (AFRIF)". He is secretary of this association.
- Alexandre Krupa is a member of the Inria Cost-GTAI in charge of the evaluation of the ADTs ("Actions de développments technologiques")

9.1.8. Animation at the regional and local levels

- Eric Marchand is in the board of the "Images et réseaux" competitivity cluster.
- Alexandre Krupa is a member of the GestChir project at the IRT B-Com in Rennes.
- Eric Marchand is a member of the scientific council of the "École supérieure d'ingénieurs de Rennes" (ESIR).

- François Chaumette is the president of the committee in charge of all the temporary recruitments ("Commission Personnel") at Inria Rennes-Bretagne Atlantique and Irisa. He is also a member of the Head team of Inria Rennes-Bretagne Atlantique.
- Eric Marchand is a member of the committee in charge of all the temporary recruitments ("Commission Personnel") at Inria Rennes-Bretagne Atlantique and Irisa. He is particularly in charge of Irisa Ph.D. students.
- Marie Babel is a member of the "Comité de centre" of Inria Rennes-Bretagne Atlantique.
- Fabien Spindler is a member of the "Commission développement durable" of Inria Rennes-Bretagne Atlantique.
- Alexandre Krupa is a member of the CUMIR ("Commission des Utilisateurs des Moyens Informatiques pour la Recherche") of Inria Rennes-Bretagne Atlantique.
- Paolo Robuffo Giordano was invited to give a talk to the M.Sc. students at the ENS Rennes in October 2014.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Marie Babel:

Master INSA3: "Statistical Signal Processing", 24 hours, M2, INSA Rennes

Master INSA1: "Assembly language compilation oriented ", 30 hours, L3, INSA Rennes

Master INSA2: "Computer science project", 30 hours, M1, INSA Rennes

Master INSA2: "Image analysis", 18 hours, M1, INSA Rennes

Master INSA1: "Remedial math courses", 24 hours, L3, INSA Rennes

Master INSA1: "Risk Management for Information Systems", 8 hours, L3, INSA Rennes

François Chaumette:

Master ESIR3: "Visual servoing", 8 hours, M2, Ecole supérieure d'ingénieurs de Rennes

Vincent Drevelle:

Master CTS: "Instrumentation, localization, GPS", 6 hours, M2, Université de Rennes 1

Master Info: "Mobile robotics", 22 hours, M2, Université de Rennes 1

Alexandre Krupa:

Master SIBM (Signals and Images in Biology and Medicine): "Medical robotics guided from images", 4.5 hours, M2, Université de Rennes 1, Brest and Angers

Master FIP TIC-Santé: "Ultrasound visual servoing", 6 hours, M2, Télécom Physique Strasbourg

Eric Marchand:

Master Esir2: "Colorimetry", 24 hours, M1, Esir Rennes

Master Esir2: "Computer vision: geometry", 24 hours, M1, Esir Rennes

Master Esir3: "Special effects", 24 hours, M2, Esir Rennes

Master Esir3: "Computer vision: tracking and recognition", 24 hours, M2, Esir Rennes

Master MRI: "Computer vision", 24 hours, M2, Université de Rennes 1

Master MIA: "Augmented reality", 4 hours, M2, Université de Rennes 1

Paolo Robuffo Giordano:

Master in Robotics: "Analysis and Control of Multi-Robot Systems", 16 hours, M2, Department of Computer and System Sciences, University of Rome "La Sapienza"

9.2.2. Supervision

Ph.D.: Bertrand Delabarre, “Contributions to dense visual tracking and visual servoing using robust similarity criteria”, defended on December 2014, supervised by Eric Marchand [8]

Ph.D.: Jérôme Ardouin, “Contribution to the study of visualization of real and virtual environment with an extended filed of view”, defended on December 2014, supervised by Anatole Lecuyer (Hybrid group in Rennes), Maud Marchal (Hybrid group) and Eric Marchand

Ph.D.: Carlo Masone, “Planning and Control for Robotic Tasks with a Human-in-the-Loop”, defended on July 2014, supervised by Paolo Robuffo Giordano with Prof. Dr.-Ing. Frank Allgöwer (University of Stuttgart) and Prof. Dr. Heinrich H. Bülthoff (Max Planck Institute for Biological Cybernetics)

Ph.D.: Volker Grabe, “Towards Robust Visual-Controlled Flight of Single and Multiple UAVs in GPS-Denied Indoor Environments”, defended on March 2014, supervised by Paolo Robuffo Giordano with Prof. Dr. Andreas Schilling (University of Tübingen) and Prof. Dr. Heinrich H. Bülthoff (Max Planck Institute for Biological Cybernetics)

Ph.D.: Rafik Sekkal, “Visual techniques for 2D object detection and tracking”, defended on February 2014, supervised by Marie Babel [9]

Ph.D. in progress: Manikandan Bakthavatchalam, “Utilisation des moments photométriques en asservissement visuel”, started in October 2011, supervised by François Chaumette

Ph.D. in progress: Tawsif Gokhool, “Représentations valides à long terme pour la navigation et l’apprentissage des modèles 3D”, started in February 2012, supervised by Patrick Rives

Ph.D. in progress: Romain Drouilly, “Représentation hybride métrique, topologique et sémantique d’environnement 3D pour la localisation temps réel”, started in May 2012, supervised by Patrick Rives

Ph.D. in progress: Le Cui, “Nano-manipulation par asservissement visuel”, started in October 2012, supervised by Eric Marchand

Ph.D. in progress: Riccardo Spica, “Autonomous vision-based two-hand manipulation strategies for humanoid robots”, started in December 2012, supervised by Paolo Robuffo Giordano and François Chaumette

Ph.D. in progress: Lucas Royer, “Visual tool for percutaneous procedures in interventional radiology”, started in September 2013, supervised by Alexandre Krupa, Maud Marchal (Hybrid group at Inria Rennes-Bretagne Atlantique and Irisa) and Guillaume Dardenne (IRT B-Com)

Ph.D. in progress: Pierre Chatelain, “Multi-modal visual servoing for intra-operative imaging”, started in September 2013, supervised by Alexandre Krupa and Nassir Navab (Technische Universität München)

Ph.D. in progress: Vishnu Karakkat Narayanan, “Semi-autonomous navigation of a wheelchair by visual servoing and user intention analysis”, started in September 2013, supervised by Marie Babel and Anne Spalanzani (e-Motion group at Inria Rhône-Alpes)

Ph.D. in progress: Suman Raj Bista, “Visual navigation of a humanoid robot”, started in October 2013, supervised by Paolo Robuffo Giordano and François Chaumette

Ph.D. in progress: Nicolas Cazy, “Model predictive visual servoing of a humanoid robot”, started in October 2013, supervised by Paolo Robuffo Giordano, François Chaumette and Pierre-Brice Wieber (Bipop group at Inria Rhône-Alpes)

Ph.D. in progress: Renato José Martins, “Robust navigation and control of an autonomous vehicle”, started in November 2013, supervised by Patrick Rives and Samuel Siqueira Bueno (CTI)

Ph.D. in progress: Aly Magassouba, “Audio-based control”, started in December 2013, supervised by François Chaumette and Nancy Bertin (Panama group at Inria Rennes-Bretagne Atlantique and Irisa)

Ph.D. in progress: Jason Chevrie, "Control of a flexible needle by visual servoing using B-mode ultrasound images", started in September 2014, supervised by Alexandre Krupa and Marie Babel

Ph.D. in progress: Quentin Bateux, "Visual servoing from global descriptors", started in October 2014, supervised by Eric Marchand

Ph.D. in progress: Fabrizio Schiano, "Collective control with onboard sensors for multiple quadrotor UAVs", started in October 2014, supervised by Paolo Robuffo Giordano

Ph.D. in progress: Pedro Patlan-Rosales, "Robotic insertion of a biopsy needle by visual servoing using elastography images", started in October 2014, supervised by Alexandre Krupa

Ph.D. in progress: Noël Mériaux, "Landing by visual servoing", started in October 2014, supervised by François Chaumette, Eric Marchand and Patrick Rives

Ph.D. in progress: Lesley-Ann Duflot, "Soft tissue deformation tracking using optical coherence tomography (OCT) and ultrasound imaging", started in November 2014, supervised by Alexandre Krupa and Brahim Tamadazte (Minarob group at FEMTO-ST, Besançon)

Master internship: Clément Leboullenger from Insa Rennes, "Haptic guidance for vision-based semi-autonomous wheelchair navigation", supervised by Marie Babel and Maud Marchal (Hybrig group at Inria Rennes-Bretagne Atlantique)

Master internship: Quentin Bateux from Insa Rouen, "Visual servoing from histograms", supervised by Eric Marchand

Master internship: Jason Chevrie from Normale Sup Cachan, "3D deformable target tracking in ultrasound images", supervised by Alexandre Krupa and Marie Babel

Bachelor internship: David Roszczypala from Univ. Rennes 1, "Target tracking by visual servoing", supervised by François Chaumette

Bachelor internship: Olivier Bordron from Normale Sup Rennes, "Active SfM with a human-in-the-loop", supervised by P. Robuffo Giordano

Bachelor internship: Quentin Delamare from Normale Sup Rennes, "Learning-based flight control for quadrotor UAVs", supervised by Paolo Robuffo Giordano

9.2.3. Juries

- Marie Babel: Jesus-Arturo Escobedo-Cabello (Ph.D., reviewer, Inria, Grenoble)
- François Chaumette: Dorra Larnaout (Ph.D., reviewer, CEA, Saclay), Ivan Markovic (Ph.D., Zagreb), Mohammed Rédha Benachenhou (Ph.D., reviewer, IRCCyN, Nantes), Dao Xuan Quy (Ph.D., Inria, Rennes), Guillaume Sabiron (Ph.D., president, Onera, Toulouse), Omar Tahri (HdR, Institut Pascal, Clermont-Ferrand), Xavier Savatier (HdR, reviewer, Irseem, Rouen)
- Eric Marchand: Ali Mekkonnen (Ph.D., reviewer, Laas, Toulouse), Maxime Boucher (Ph.D., Evry), Olivier Le Meur (HdR, Irisa, Rennes), Rémi Cozot (HDR, president, Irisa, Rennes), Valérie Renaudin (HdR, president, Irstea), Clément Deymier (Ph.D., president, Institut Pascal, Clermont-Ferrand), Mihir Jain (Ph.D., president, Irisa, Rennes)
- Patrick Rives: : R. Marie (Ph.D., Mis Amiens), E. Wirbel (Ph.D., president, Ecole des Mines de Paris), J.C. Devaux (Ph.D., reviewer, Ibisc Evry), G. Bernardes Vitor (Ph.D., reviewer, Unicamp Brazil), Xavier Savatier (HdR, president, Irseem, Rouen)

9.2.4. Patent

- Paolo Robuffo Giordano obtained the US Patent N. 8,634,969 "Teleoperation Method And Human Robot Interface For Remote Control of a Machine by a Human Operator" with Prof. Dr. Heinrich H. Bülthoff (Max Planck Institute for Biological Cybernetics)

9.3. Popularization

- Due to the visibility of our experimental platforms, the team is often asked to present its research activities to students, researchers or industry. Our panel of demonstrations allows us to highlight recent results concerning the positioning of an ultrasound probe by visual servoing, the construction of a tower by combining 3D model-based visual tracking and visual servoing techniques to pick up cubes that are assembled, vision-based detection and tracking for space navigation in a rendezvous context, the semi-autonomous navigation of a wheelchair, and augmented reality applications.
- Marie Babel and François Pasteau gave a press conference in December 2014, organized at Pôle Saint Hélier (Rennes)
- Marie Babel gave a talk on "A driving assistance solution" in October 2014, during the "Semaine des Téleécoms - Robotique et objets connectés" organised at Insa Rennes
- Fabien Spindler is a member of the editorial board of “Ouest Inria”, the internal journal at Inria Rennes-Bretagne Atlantique.

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Major publications by the team in recent years

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Doctoral Dissertations and Habilitation Theses

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[9] R. SEKKAL. *Visual techniques for 2D object detection and tracking*, INSA de Rennes, February 2014, https://tel.archives-ouvertes.fr/tel-00981107

Articles in International Peer-Reviewed Journals

[10] G. CARON, A. DAME, E. MARCHAND. *Direct model based visual tracking and pose estimation using mutual information*, in "Image and Vision Computing", January 2014, vol. 32, n^{o} 1, pp. 54-63 [*DOI :* 10.1016/J.IMAVIS.2013.10.007], https://hal.inria.fr/hal-00879104

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