



Activity Report 2018

Team RAINBOW

Sensor-based Robotics and Human Interaction

Joint team with Inria Rennes – Bretagne Atlantique

D5 – Digital Signals and Images, Robotics



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Project-Team RAINBOW

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Keywords:

Computer Science and Digital Science:

- A5.1.3. - Haptic interfaces
- A5.1.7. - Multimodal interfaces
- A5.4.4. - 3D and spatio-temporal reconstruction
- A5.4.6. - Object localization
- A5.4.7. - Visual servoing
- A5.6.2. - Augmented reality
- A5.6.3. - Avatar simulation and embodiment
- A5.6.4. - Multisensory feedback and interfaces
- A5.9.2. - Estimation, modeling
- A5.10.2. - Perception
- A5.10.3. - Planning
- A5.10.4. - Robot control
- A5.10.5. - Robot interaction (with the environment, humans, other robots)
- A5.10.6. - Swarm robotics
- A6.4.1. - Deterministic control
- A6.4.3. - Observability and Controlability
- A6.4.4. - Stability and Stabilization
- A6.4.5. - Control of distributed parameter systems
- A6.4.6. - Optimal control

Other Research Topics and Application Domains:

- B2.4.3. - Surgery
- B2.5. - Handicap and personal assistances
- B5.1. - Factory of the future
- B5.6. - Robotic systems
- B8.1.2. - Sensor networks for smart buildings
- B8.4. - Security and personal assistance

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2. Overall Objectives

2.1. Overall Objectives

The long-term vision of the Rainbow team is to develop the next generation of sensor-based robots able to navigate and/or interact in complex unstructured environments *together* with human users. Clearly, the word “together” can have very different meanings depending on the particular context: for example, it can refer to mere co-existence (robots and humans share some space while performing independent tasks), human-awareness (the robots need to be aware of the human state and intentions for properly adjusting their actions), or actual cooperation (robots and humans perform some shared task and need to coordinate their actions).

One could perhaps argue that these two goals are somehow in conflict since higher robot autonomy should imply lower (or absence of) human intervention. However, we believe that our general research direction is well motivated since: *(i)* despite the many advancements in robot autonomy, complex and high-level cognitive-based decisions are still out of reach. In most applications involving tasks in unstructured environments, uncertainty, and interaction with the physical world, human assistance is still necessary, and will most probably be for the next decades. On the other hand, robots are extremely capable at autonomously executing specific and repetitive tasks, with great speed and precision, and at operating in dangerous/remote environments, while humans possess unmatched cognitive capabilities and world awareness which allow them to take complex and quick decisions; *(ii)* the cooperation between humans and robots is often an implicit constraint of the robotic task itself. Consider for instance the case of assistive robots supporting injured patients during their physical recovery, or human augmentation devices. It is then important to study proper ways of implementing this cooperation; *(iii)* finally, safety regulations can require the presence at all times of a person in charge of supervising and, if necessary, take direct control of the robotic workers. For example, this is a common requirement in all applications involving tasks in public spaces, like autonomous vehicles in crowded spaces, or even UAVs when flying in civil airspace such as over urban or populated areas.

Within this general picture, the Rainbow activities will be particularly focused on the case of **(shared) cooperation between robots and humans** by pursuing the following vision: on the one hand, empower robots with a *large degree of autonomy* for allowing them to effectively operate in non-trivial environments (e.g., outside completely defined factory settings). On the other hand, include *human users* in the loop for having them in (partial and bilateral) control of some aspects of the overall robot behavior. We plan to address these challenges from the **methodological, algorithmic** and **application-oriented** perspectives. The main *research axes* along which the Rainbow activities will be articulated are: three supporting axes (**Optimal and**

Uncertainty-Aware Sensing; Advanced Sensor-based Control; Haptics for Robotics Applications) that are meant to develop methods, algorithms and technologies for realizing the central theme of **Shared Control of Complex Robotic Systems**.

3. Research Program

3.1. Main Vision

The vision of Rainbow (and foreseen applications) calls for several general scientific challenges: *(i)* high-level of autonomy for complex robots in complex (unstructured) environments, *(ii)* forward interfaces for letting an operator giving high-level commands to the robot, *(iii)* backward interfaces for informing the operator about the robot ‘status’, *(iv)* user studies for assessing the best interfacing, which will clearly depend on the particular task/situation. Within Rainbow we plan to tackle these challenges at different levels of depth:

- the **methodological and algorithmic side** of the sought human-robot interaction will be the **main focus** of Rainbow. Here, by also exploiting the previous Lagadic expertise, we will be interest in advancing the state-of-the-art in sensor-based online planning, control and manipulation for mobile/fixed robots. For instance, while classically most control approaches (especially those sensor-based) have been essentially *reactive*, we believe that less myopic strategies based on online/reactive trajectory optimization will be needed for the future Rainbow activities. The core ideas of Model-Predictive Control approaches (also known as Receding Horizon) or, in general, numerical optimal control methods will play a role in the Rainbow activities, for allowing the robots to reason/plan over some future time window and better cope with constraints. We will also consider extending classical sensor-based motion control/manipulation techniques to more realistic scenarios, such as deformable/flexible objects (“**Advanced Sensor-based Control**” axis). Finally, it will also be important to spend research efforts into the field of *Optimal Sensing*, in the sense of generating (again) trajectories that can optimize the state estimation problem in presence of scarce sensory inputs and/or non-negligible measurement and process noises, especially true for the case of mobile robots (“**Optimal and Uncertainty-Aware Sensing**” axis). We also aim at addressing the case of coordination between a single human user and multiple robots where, clearly, as explained the autonomy part plays even a more crucial role (no human can control multiple robots at once, thus a high degree of autonomy will be required by the robot group for executing the human commands);
- the **interfacing side** will also be a focus of the Rainbow activities. As explained above, we will be interested in both the *forward* (human \rightarrow robot) and *backward* (robot \rightarrow human) interfaces. The forward interface will be mainly addressed from the *algorithmic* point of view, i.e., how to map the few degrees of freedom available to a human operator (usually in the order of 3–4) into complex commands for the controlled robot(s). This mapping will typically be mediated by an “AutoPilot” onboard the robot(s) for autonomously assessing if the commands are feasible and, if not, how to least modify them (“**Advanced Sensor-based Control**” axis).

The backward interface will, instead, mainly consist of a visual/haptic feedback for the operator. Here, we aim at exploiting our expertise in using force cues for informing an operator about the status of the remote robot(s). However, the sole use of classical *grounded* force feedback devices (e.g., the typical force-feedback joysticks) will not be enough due to the different kinds of information that will have to be provided to the operator. In this context, the recent interest in the use of *wearable* haptic interfaces is very interesting and will be investigated in depth (these include, e.g., devices able to provide vibro-tactile information to the fingertips, wrist, or other parts of the body). The main challenges in these activities will be the mechanical conception (and construction) of suitable wearable interfaces for the tasks at hand, and in the generation of force cues for the operator: the force cues will be a (complex) function of the robot state, therefore motivating research in algorithms for mapping the robot state into a few variables (the force cues) (“**Haptics for Robotics Applications**” axis);

- the **evaluation side** that will assess the proposed interfaces with some user studies, or acceptability studies by human subjects. Although this activity **will not** be a main focus of Rainbow (complex user studies are beyond the scope of our core expertise), we will nevertheless devote some efforts into having some reasonable level of user evaluations by applying standard statistical analysis based on psychophysical procedures (e.g., randomized tests and Anova statistical analysis). This will be particularly true for the activities involving the use of smart wheelchairs, which are intended to be used by human users *and* operate inside human crowds. Therefore, we will be interested in gaining some level of understanding of how semi-autonomous robots (a wheelchair in this example) can predict the human intention, and how humans can react to a semi-autonomous mobile robot.

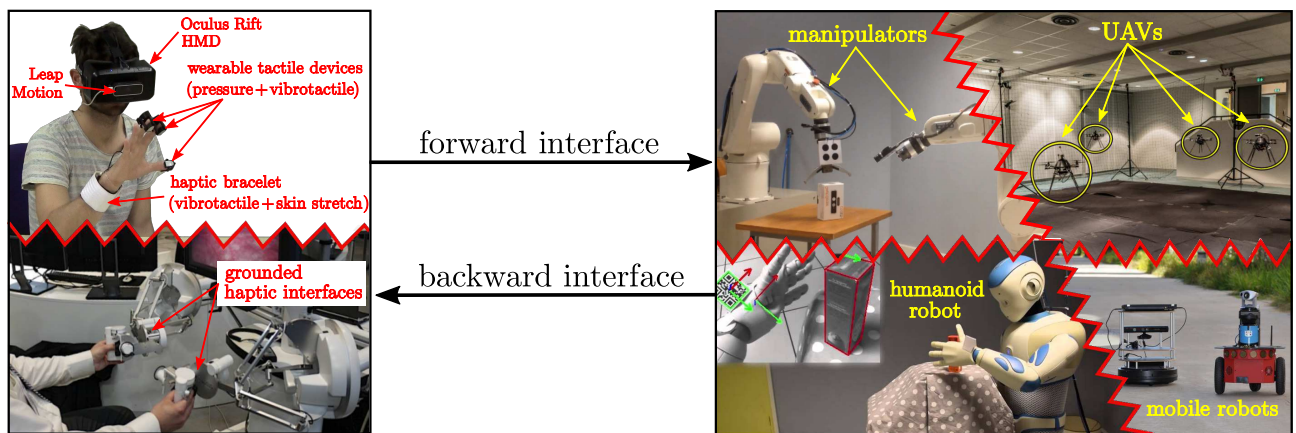


Figure 1. An illustration of the prototypical activities foreseen in Rainbow in which a human operator is in partial (and high-level) control of single/multiple complex robots performing semi-autonomous tasks

Figure 1 depicts in an illustrative way the *prototypical* activities foreseen in Rainbow. On the righthand side, complex robots (dual manipulators, humanoid, single/multiple mobile robots) need to perform some task with high degree of autonomy. On the lefthand side, a human operator gives some high-level commands and receives a visual/haptic feedback aimed at informing her/him at best of the robot status. Again, the main challenges that Rainbow will tackle to address these issues are (in order of relevance): (i) methods and algorithms, mostly based on first-principle modeling and, when possible, on numerical methods for online/reactive trajectory generation, for enabling the robots with high autonomy; (ii) design and implementation of visual/haptic cues for interfacing the human operator with the robots, with a special attention to novel combinations of grounded/ungrounded (wearable) haptic devices; (iii) user and acceptability studies.

3.2. Main Components

Hereafter, a summary description of the four axes of research in Rainbow.

3.2.1. Optimal and Uncertainty-Aware Sensing

Future robots will need to have a large degree of autonomy for, e.g., interpreting the sensory data for accurate estimation of the robot and world state (which can possibly include the human users), and for devising motion plans able to take into account many constraints (actuation, sensor limitations, environment), including also the state estimation accuracy (i.e., how well the robot/environment state can be reconstructed from the sensed data). In this context, we will be particularly interested in (i) devising trajectory optimization strategies able to maximize some norm of the information gain gathered along the trajectory (and with the

available sensors). This can be seen as an instance of Active Sensing, with the main focus on *online/reactive* trajectory optimization strategies able to take into account several requirements/constraints (sensing/actuation limitations, noise characteristics). We will also be interested in the coupling between optimal sensing and concurrent execution of additional tasks (e.g., navigation, manipulation). *(ii)* Formal methods for guaranteeing the accuracy of localization/state estimation in mobile robotics, mainly exploiting tools from interval analysis. The interest in these methods is their ability to provide possibly conservative but guaranteed accuracy bounds on the best accuracy one can obtain with the given robot/sensor pair, and can thus be used for planning purposes of for system design (choice of the best sensor suite for a given robot/task). *(iii)* Localization/tracking of objects with poor/unknown or deformable shape, which will be of paramount importance for allowing robots to estimate the state of “complex objects” (e.g., human tissues in medical robotics, elastic materials in manipulation) for controlling its pose/interaction with the objects of interest.

3.2.2. *Advanced Sensor-based Control*

One of the main competences of the previous Lagadic team has been, generally speaking, the topic of *sensor-based control*, i.e., how to exploit (typically onboard) sensors for controlling the motion of fixed/ground robots. The main emphasis has been in devising ways to directly couple the robot motion with the sensor outputs in order to invert this mapping for driving the robots towards a configuration specified as a desired sensor reading (thus, directly in sensor space). This general idea has been applied to very different contexts: mainly standard vision (from which the Visual Servoing keyword), but also audio, ultrasound imaging, and RGB-D.

Use of sensors for controlling the robot motion will also clearly be a central topic of the Rainbow team too, since the use of (especially onboard) sensing is a main characteristics of any future robotics application (which should typically operate in unstructured environments, and thus mainly rely on its own ability to sense the world). We then naturally aim at making the best out of the previous Lagadic experience in sensor-based control for proposing new advanced ways of exploiting sensed data for, roughly speaking, controlling the motion of a robot. In this respect, we plan to work on the following topics: *(i)* “direct/dense methods” which try to directly exploit the raw sensory data in computing the control law for positioning/navigation tasks. The advantages of these methods is the need for little data pre-processing which can minimize feature extraction errors and, in general, improve the overall robustness/accuracy (since all the available data is used by the motion controller); *(ii)* sensor-based interaction with objects of unknown/deformable shapes, for gaining the ability to manipulate, e.g., flexible objects from the acquired sensed data (e.g., controlling online a needle being inserted in a flexible tissue); *(iii)* sensor-based model predictive control, by developing *online/reactive* trajectory optimization methods able to plan feasible trajectories for robots subjects to sensing/actuation constraints with the possibility of (onboard) sensing for continuously replanning (over some future time horizon) the optimal trajectory. These methods will play an important role when dealing with complex robots affected by complex sensing/actuation constraints, for which pure reactive strategies (as in most of the previous Lagadic works) are not effective. Furthermore, the coupling with the aforementioned optimal sensing will also be considered; *(iv)* multi-robot decentralised estimation and control, with the aim of devising again sensor-based strategies for groups of multiple robots needing to maintain a formation or perform navigation/manipulation tasks. Here, the challenges come from the need of devising “simple” decentralized and scalable control strategies under the presence of complex sensing constraints (e.g., when using onboard cameras, limited fov, occlusions). Also, the need of locally estimating global quantities (e.g., common frame of reference, global property of the formation such as connectivity or rigidity) will also be a line of active research.

3.2.3. *Haptics for Robotics Applications*

In the envisaged *shared* cooperation between human users and robots, the typical sensory channel (besides vision) exploited to inform the human users is most often the force/kinesthetic one (in general, the sense of touch and of applied forces to the human hand or limbs). Therefore, a part of our activities will be devoted to study and advance the use of *haptic* cueing algorithms and interfaces for providing a feedback to the users during the execution of some shared task. We will consider: *(i)* multi-modal haptic cueing for general teleoperation applications, by studying how to convey information through the kinesthetic and cutaneous channels. Indeed, most haptic-enabled applications typically only involve kinesthetic cues, e.g., the

forces/torques that can be felt by grasping a force-feedback joystick/device. These cues are very informative about, e.g., preferred/forbidden motion directions, but are also inherently limited in their resolution since the kinesthetic channel can easily become overloaded (when too much information is compressed in a single cue). In recent years, the arise of novel cutaneous devices able to, e.g., provide vibro-tactile feedback on the fingertips or skin, has proven to be a viable solution to *complement* the classical kinesthetic channel. We will then study how to combine these two sensory modalities for different prototypical application scenarios, e.g., 6-dof teleoperation of manipulator arms, virtual fixtures approaches, and remote manipulation of (possibly deformable) objects; *(ii)* in the particular context of medical robotics, we plan to address the problem of providing haptic cues for typical medical robotics tasks, such as semi-autonomous needle insertion and robot surgery by exploring the use of kinesthetic feedback for rendering the mechanical properties of the tissues, and vibrotactile feedback for providing with guiding information about pre-planned paths (with the aim of increasing the usability/acceptability of this technology in the medical domain); *(iii)* finally, in the context of multi-robot control we would like to explore how to use the haptic channel for providing information about the status of *multiple* robots executing a navigation or manipulation task. In this case, the problem is (even more) how to map (or compress) information about many robots into a few haptic cues. We plan to use specialized devices, such as actuated exoskeleton gloves able to provide cues to each fingertip of a human hand, or to resort to “compression” methods inspired by the *hand postural synergies* for providing coordinated cues representative of a few (but complex) motions of the multi-robot group, e.g., coordinated motions (translations/expansions/rotations) or collective grasping/transporting.

3.2.4. Shared Control of Complex Robotics Systems

This final and main research axis will exploit the **methods, algorithms and technologies** developed in the previous axes for realizing applications involving complex semi-autonomous robots operating in complex environments together with human users. The *leitmotiv* is to realize advanced *shared control* paradigms, which essentially aim at blending robot autonomy and user’s intervention in an optimal way for exploiting the best of both worlds (robot accuracy/sensing/mobility/strength and human’s cognitive capabilities). A common theme will be the issue of where to “draw the line” between robot autonomy and human intervention: obviously, there is no general answer, and any design choice will depend on the particular task at hand and/or on the technological/algorithmic possibilities of the robotic system under consideration.

A *prototypical* envisaged application, exploiting and combining the previous three research axes, is as follows: a complex robot (e.g., a two-arm system, a humanoid robot, a multi-UAV group) needs to operate in an environment exploiting its onboard sensors (in general, vision as the main exteroceptive one) and deal with many constraints (limited actuation, limited sensing, complex kinematics/dynamics, obstacle avoidance, interaction with difficult-to-model entities such as surrounding people, and so on). The robot must then possess a quite large autonomy for interpreting and exploiting the sensed data in order to estimate its own state and the environment one (“**Optimal and Uncertainty-Aware Sensing**” axis), and for planning its motion in order to fulfil the task (e.g., navigation, manipulation) by coping with all the robot/environment constraints. Therefore, advanced control methods able to exploit the sensory data at its most, and able to cope *online* with constraints in an optimal way (by, e.g., continuously replanning and predicting over a future time horizon) will be needed (“**Advanced Sensor-based Control**” axis), with a possible (and interesting) coupling with the sensing part for optimizing, at the same time, the state estimation process. Finally, a human operator will typically be in charge of providing high-level commands (e.g., where to go, what to look at, what to grasp and where) that will then be autonomously executed by the robot, with possible local modifications because of the various (local) constraints. At the same time, the operator will also receive *online* visual-force cues informative of, in general, how well her/his commands are executed and if the robot would prefer or suggest other plans (because of the local constraints that are not of the operator’s concern). This information will have to be visually and haptically rendered with an optimal combination of cues that will depend on the particular application (“**Haptics for Robotics Applications**” axis).

4. Application Domains

4.1. Application Domains

The activities of Rainbow falls obviously within the scope of Robotics. Broadly speaking, our main interest in in devising novel/efficient *algorithms* (for estimation, planning, control, haptic cueing, human interfacing, etc.) that can be general and applicable to many different robotic systems of interest, depending on the particular application/case study. For instance, we plan to consider

- applications involving remote telemanipulation with one or two robot arms, where the arm(s) will need to coordinate their motion for approaching/grasping objects of interest under the guidance of a human operator;
- applications involving single and multiple mobile robots for spatial navigation tasks (e.g., exploration, surveillance, mapping). In the multi-robot case, the high redundancy of the multi-robot group will motivate research in autonomously exploiting this redundancy for facilitating the task (e.g., optimizing the self-localization of the environment mapping) while following the human commands, and vice-versa for informing the operator about the status of a multi-robot group. In the single robot case, the possible combination with some manipulation devices (e.g., arms on a wheeled robot) will motivate research into remote tele-navigation and tele-manipulation;
- applications involving medical robotics, in which the “manipulators” are replaced by the typical tools used in medical applications (ultrasound probes, needles, cutting scalpels, and so on) for semi-autonomous probing and intervention;
- applications involving a direct physical “coupling” between human users and robots (rather than a “remote” interfacing), such as the case of assistive devices used for easing the life of impaired people. Here, we will be primarily interested in, e.g., safety and usability issues, and also touch some aspects of user acceptability.

These directions are, in our opinion, very promising since nowadays and future robotics applications are expected to address more and more complex tasks: for instance, it is becoming mandatory to empower robots with the ability to predict the future (to some extent) by also explicitly dealing with uncertainties from sensing or actuation; to safely and effectively interact with human supervisors (or collaborators) for accomplishing shared tasks; to learn or adapt to the dynamic environments from small prior knowledge; to exploit the environment (e.g., obstacles) rather than avoiding it (a typical example is a humanoid robot in a multi-contact scenario for facilitating walking on rough terrains); to optimize the onboard resources for large-scale monitoring tasks; to cooperate with other robots either by direct sensing/communication, or via some shared database (the “cloud”).

While no single lab can reasonably address all these theoretical/algorithmic/technological challenges, we believe that our research agenda can give some concrete contributions to the next generation of robotics applications.

5. Highlights of the Year

5.1. Highlights of the Year

- Julien Pettré is coordinator of the H2020 ICT CrowdBot project which started in Jan 2018
- Claudio Pacchierotti is the unit PI of the new H2020 FET-OPEN project “H-Reality,” started on October 2018. The project gathers 5 academic partners - Univ. Birmingham (UK, coordinator), TU Delft (NL), CNRS (France) - as well as 2 industrial partners - Ultrahaptics (UK) and Actronika SAS (France)
- Claudio Pacchierotti has been elected Secretary of the Eurohaptics Society

5.1.1. Awards

- Firas Abi Farraj was finalist for the IEEE/RSJ IROS 2018 Best Paper Award on Safety, Security and Rescue Robotics

- Claudio Pacchierotti has been selected as “Top 1% Reviewer” by field, 2018 Peer Review Awards, Publons (<https://publons.com/awards/2018/esi/?name=Pacchierotti&esi=23>)
- Louise Devigne was one of the five finalists of Best Paper Award for the IEEE SMC 2018 conference for the paper [60]
- Louise Devigne received the Best Paper Award of the IFRATH Handicap 2018 conference [80]
- Salma Jiddi received the Best Demo Award at the Asia Pacific Workshop on Mixed and Augmented Reality, APMAR’18, Taipei, Taiwan [63]

6. New Software and Platforms

6.1. bib2html

Latex bibliography generator

KEYWORDS: LaTeX - Bibliography

FUNCTIONAL DESCRIPTION: The purpose of this software is to automatically produce html pages from BibTEX files, and to provide access to the BibTEX entries by several criteria: year of publication, category of publication, keywords, author name. Moreover cross-linking is generating between pages to provide an easy navigation through the pages without going back to the index.

- Partners: Inria - Université de Rennes 1
- Contact: Éric Marchand
- URL: <http://www.irisa.fr/lagadic/soft/bib2html/bib2html.html>

6.2. HandiViz

Driving assistance of a wheelchair

KEYWORDS: Health - Persons attendant - Handicap

FUNCTIONAL DESCRIPTION: 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.

- Participants: François Pasteau and Marie Babel
- Partner: INSA Rennes
- Contact: Marie Babel

6.3. SINATRACK

Model-based visual tracking of complex objects

KEYWORDS: Computer vision - Robotics

FUNCTIONAL DESCRIPTION: Sinatrack is a tracking software that allows the 3D localization (translation and rotation) of an object with respect to a monocular camera. It allows to consider object with complex shape. The underlying approach is a model-based tracking techniques. It has been developed for satellite localization and on-orbit service applications but is also suitable for augmented reality purpose.

- Participants: Antoine Guillaume Petit, Éric Marchand and François Chaumette
- Partners: Inria - Université de Rennes 1
- Contact: Éric Marchand

6.4. UsTk

Ultrasound toolkit for medical robotics applications guided from ultrasound images

KEYWORDS: Echographic imagery - Image reconstruction - Medical robotics - Visual tracking - Visual servoing (VS) - Needle insertion

FUNCTIONAL DESCRIPTION: UsTK, standing for Ultrasound Toolkit, is a cross-platform extension of ViSP software dedicated to two- (2D) and three-dimensional (3D) ultrasound image processing and visual servoing based on ultrasound images. Written in C++, UsTK architecture provides a core module that implements all the data structures at the heart of UsTK, a grabber module that allows to acquire ultrasound images from an Ultrasonix or a Sonosite device, a GUI module to display data, an IO module for providing functionalities to read/write data from a storage device, and a set of image processing modules to compute the confidence map of ultrasound images, generate elastography images, track a flexible needle in sequences of 2D and 3D ultrasound images and track a target image template in sequences of 2D ultrasound images. All these modules were implemented on several robotic demonstrators to control the motion of an ultrasound probe or a flexible needle by ultrasound visual servoing.

- Participants: Alexandre Krupa, Marc Pouliquen, Fabien Spindler and Pierre Chatelain
- Partners: Inria - Université de Rennes 1
- Contact: Alexandre Krupa
- URL: <https://ustk.inria.fr>

6.5. ViSP

Visual servoing platform

KEYWORDS: Augmented reality - Computer vision - Robotics - Visual servoing (VS) - Visual tracking

SCIENTIFIC DESCRIPTION: Since 2005, we develop and release ViSP [1], an open source library available from <https://visp.inria.fr>. ViSP standing for Visual Servoing Platform allows prototyping and developing applications using visual tracking and visual servoing techniques at the heart of the Rainbow research. ViSP was designed to be independent from 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...) or 3D model-based tracking of known objects or template tracking. Simulation capabilities are also available.

[1] E. Marchand, F. Spindler, F. Chaumette. ViSP for visual servoing: a generic software platform with a wide class of robot control skills. IEEE Robotics and Automation Magazine, Special Issue on "Software Packages for Vision-Based Control of Motion", P. Oh, D. Burschka (Eds.), 12(4):40-52, December 2005.

FUNCTIONAL DESCRIPTION: ViSP provides simple ways to integrate and validate new algorithms with already existing tools. It follows a module-based software engineering design where data types, algorithms, sensors, viewers and user interaction are made available. Written in C++, ViSP is based on open-source cross-platform libraries (such as OpenCV) and builds with CMake. Several platforms are supported, including OSX, iOS, Windows and Linux. ViSP online documentation allows to ease learning. More than 300 fully documented classes organized in 17 different modules, with more than 380 examples and 82 tutorials are proposed to the user. ViSP is released under a dual licensing model. It is open-source with a GNU GPLv2 or more recent license. A professional edition license that replaces GNU GPLv2 is also available.

- Participants: Aurélien Yol, Éric Marchand, Fabien Spindler, François Chaumette and Souriya Trinh
- Partners: Inria - Université de Rennes 1
- Contact: Fabien Spindler
- URL: <http://visp.inria.fr>

6.6. Platforms

6.6.1. Robot Vision Platform

Participants: François Chaumette, Fabien Spindler [contact].

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 6 DoF Gantry robot, the other one is a 4 DoF cylindrical robot (see Fig. 2). These robots are equipped with cameras. The Gantry robot also allows embedding grippers on its end-effector.

Note that 3 papers [53], [78], [10] and 1 PhD Thesis [2] published by Rainbow in 2018 include results validated on this platform.



Figure 2. Rainbow robotics platform for vision-based manipulation

6.6.2. Mobile Robots

Participants: Marie Babel, Solenne Fortun, François Pasteau, Fabien Spindler [contact].

For fast prototyping of algorithms in perception, control and autonomous navigation, the team uses a Pioneer 3DX from Adept (see Fig. 3.a). This platform is equipped with various sensors needed for autonomous navigation and sensor-based control.

Moreover, to validate our research in personally assisted living topic (see Section 7.4.3), we have three electric wheelchairs, one from Permobil, one from Sunrise and the last from YouQ (see Fig. 3.b). 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 ultrasound sensors to perform the required servoing for assisting handicapped people. This year we also bought a wheelchair haptic simulator to develop new human interaction strategies in an virtual reality environment (Fig. 3(c)).

Note that 4 papers exploiting the mobile robots were published this year [23], [60], [79], [80].

6.6.3. Medical Robotic Platform

Participants: Alexandre Krupa, Marc Pouliquen, Fabien Spindler [contact].

This platform is composed of two 6 DoF Adept Viper 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. The haptic Virtuose 6D device (see Fig. 8.a) can also be used within this platform.



Figure 3. Mobile Robot Platform. a) Pioneer P3-DX robot, b) wheelchairs from Permobil, Sunrise and YouQ, c) the wheelchair haptic simulator.

This testbed is of primary interest for researches and experiments concerning ultrasound visual servoing applied to probe positioning, soft tissue tracking, elastography or robotic needle insertion tasks (see Section 7.2.9).

This platform was used to obtain experimental results presented in 6 articles [18], [61], [12], [10], [36], [51] and in 2 PhD manuscripts [4], [5] published this year.

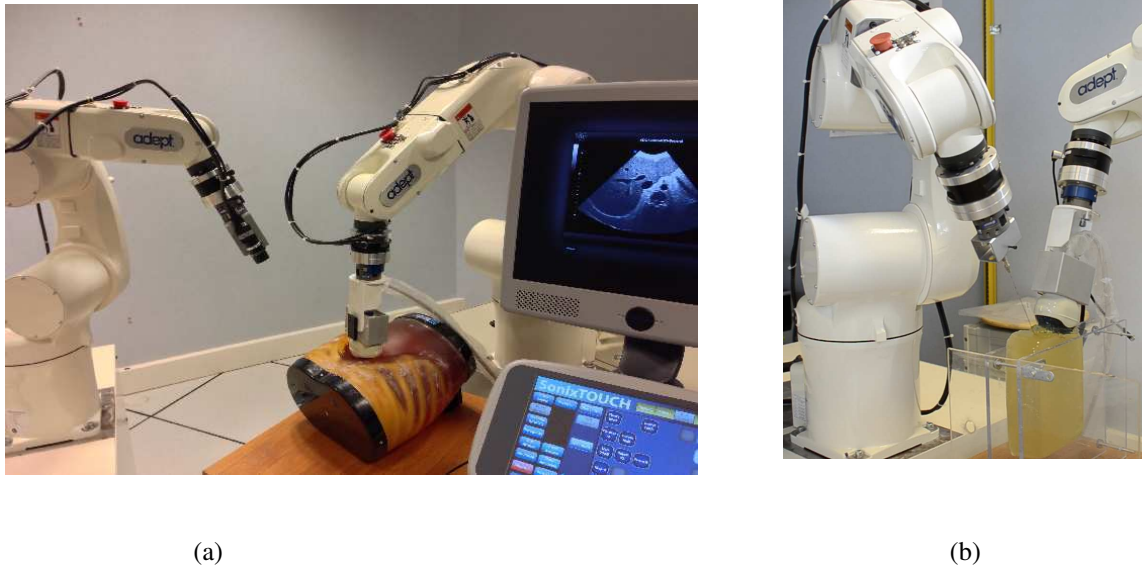


Figure 4. Rainbow medical robotic platforms. a) On the right Viper S850 robot arm equipped with a SonixTouch 3D ultrasound probe. On the left Viper S650 equipped with a tool changer that allows to attach a classical camera or biopsy needles. b) Robotic setup for autonomous needle insertion by visual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

6.6.4. Advanced Manipulation Platform

Participants: François Chaumette, Claudio Pacchierotti, Paolo Robuffo Giordano, Fabien Spindler [contact].

This new platform is composed by 2 Panda lightweight arms from **Franka Emika** equipped with torque sensors in all seven axes. An electric gripper, a camera or a soft hand from **qbrobotics** can be mounted on the robot end-effector (see Fig. 5) to validate our researches in coupling force and vision for controlling robot manipulators (see Section 7.2.13) and in shared control for remote manipulation (see Section 7.4.1). Other haptic devices (see Section 6.6.7) can also be coupled to this platform.

Note that 1 paper published this year include experimental results obtained with new platform [77].



Figure 5. Rainbow advanced manipulation platform. One of the two Panda lightweight arms from Franka Emika, with mounted the Pisa SoftHand.

6.6.5. Humanoid Robots

Participants: François Chaumette, Julien Pettré, Fabien Spindler [contact].

Romeo is a humanoid robot from SoftBank Robotics which is intended to be a genuine personal assistant and companion. Only the upper part of the body (trunk, arms, neck, head, eyes) is working. This research platform is used to validate our researches in visual servoing and visual tracking for object manipulation (see Fig. 6.a).

Pepper, another human-shaped robot designed by SoftBank Robotics to be a genuine day-to-day companion (see Fig. 6.b) is also part of this platform. It has 17 DoF mounted on a wheeled holonomic base and a set of sensors (cameras, laser, ultrasound, inertial, microphone) that makes this platform interesting for robot-human interactions during locomotion (see Section 7.2.5).

Note that 2 papers published this year include experimental results obtained with this platform [24], [23].

6.6.6. Unmanned Aerial Vehicles (UAVs)

Participants: Pol Mordel, Paolo Robuffo Giordano, Fabien Spindler [contact].

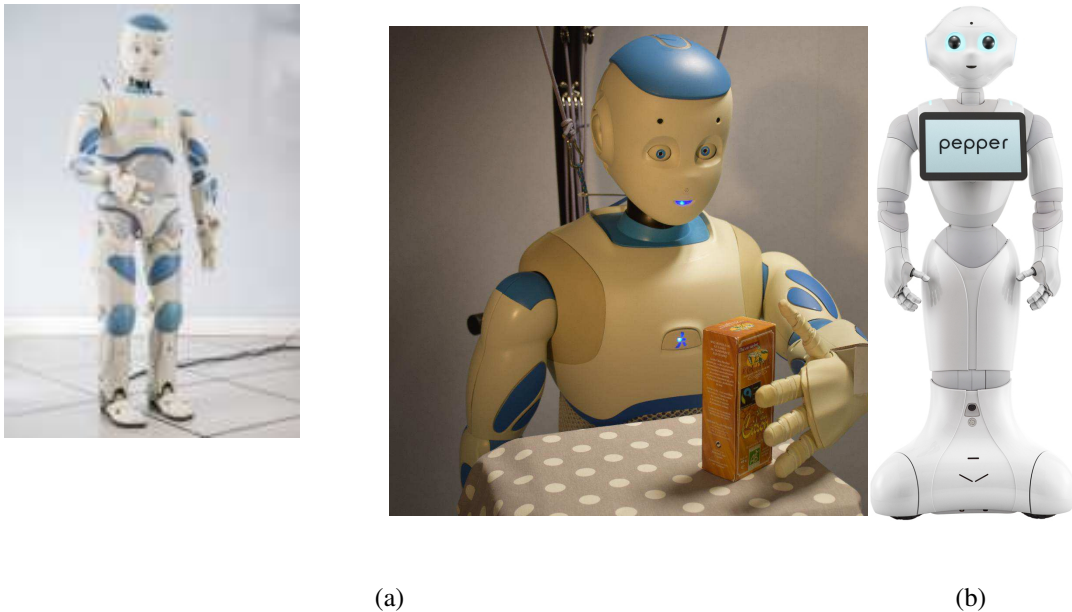


Figure 6. Humanoid Robots Platform. a) Romeo experimental platform, b) Pepper human-shaped robot

From 2014, Rainbow also started some activities involving perception and control for single and multiple quadrotor UAVs, especially thanks to the ANR project “SenseFly” (see Section 9.2.1). To this end, we purchased four quadrotors from Mikrokopter GmbH, Germany (see Fig. 7.a), and one quadrotor from 3DRobotics, USA (see Fig. 7.b). The Mikrokopter quadrotors have been heavily customized by: (i) reprogramming from scratch the low-level attitude controller onboard the microcontroller of the quadrotors, (ii) equipping each quadrotor with a NVIDIA Jetson TX2 board running Linux Ubuntu and the TeleKyb-3 software based on genom3 framework developed at LAAS in Toulouse (the middleware used for managing the experiment flows and the communication among the UAVs and the base station), and (iii) purchasing the Flea Color USB3 cameras together with the gimbal needed to mount them on the UAVs. The quadrotor group is 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.

This year 7 papers [33], [34], [65], [67], [72], [17], [71] and 1 PhD Thesis [7] contain experimental results obtained with this platform.

6.6.7. Haptics and Shared Control Platform

Participants: Claudio Pacchierotti, Paolo Robuffo Giordano, Fabien Spindler [contact].

Various haptic devices are used to validate our research in shared control. We have a Virtuoso 6D device from **Haption** (see Fig. 8.a). This device is used as master device in many of our shared control activities (see Sections 9.3.1.3, 7.2.10, and 7.3.1). It could also be coupled to the **Haption** haptic glove in loan from the University of Birmingham. An Omega 6 (see Fig. 8.b) from **Force Dimension**, devices in loan from **Ultrahaptics** as well as a soft hand from **qrobotics** complete this platform that could be coupled to the other robotic platforms.

This platform was used to obtain experimental results presented in 2 articles [51], [36] and in 1 PhD manuscript [5] published this year.

7. New Results



(a)



(b)

Figure 7. Unmanned Aerial Vehicles Platform. a) Quadrotor XL1 from Mikrokopter; b) Quadrotor Iris from 3DRobotics



(a)



(b)

Figure 8. Haptics and Shared Control Platform. a) Virtuose 6D and b) Omega 6 haptic devices

7.1. Optimal and Uncertainty-Aware Sensing

7.1.1. Visual Tracking for Motion Capture and virtual reality

Participants: Guillaume Cortes [Hybrid], Eric Marchand.

Considering the visual tracking system for motion proposed last year, we studied a novel approach for Mobile Spatial Augmented Reality on Tangible objects [14]. MoSART is dedicated to mobile interaction with tangible objects in single or collaborative situations. It is based on a novel ‘all-in-one’ Head-Mounted Display (AMD) including a projector (for the SAR display) and cameras (for the scene registration). Equipped with the HMD the user is able to move freely around tangible objects and manipulate them at will. The system tracks the position and orientation of the tangible 3D objects and projects virtual content over them. The tracking is a feature-based stereo optical tracking providing high accuracy and low latency. A projection mapping technique is used for the projection on the tangible objects which can have a complex 3D geometry. Several interaction tools have also been designed to interact with the tangible and augmented content, such as a control panel and a pointer metaphor, which can benefit as well from the MoSART projection mapping and

7.1.2. Deformable Object 3D Tracking based on Depth Information and Physical Model

Participants: Agniva Sengupta, Eric Marchand, Alexandre Krupa.

In the context of the iProcess project (see Section 9.3.3.2), we have developed a method for tracking rigid objects of complex shapes. This year, we started to elaborate a method to track deformable objects using a depth camera (RGB-D sensor). This method is based on the assumption that a coarse mesh representing the model of the object is known and that a simple volumetric tetrahedral mesh has been computed offline, representing the internal physical model of the object. To take into account the deformation of the object, a corotational Finite Element Method (FEM) is considered as the physical model. Given the sequential pointcloud of the object undergoing deformation, we have developed an algorithm that fits the deformable model to the observed pointcloud. The FEM simulation is done using the SOFA library and our approach was tested for the tracking of simulated deformation of objects. For the moment, the method succeeds to accurately track the object deformation, given that we know the point of application of force (causing the deformation) and the force direction vector. Online estimation of the direction vector of this force is currently a work in progress.

7.1.3. General Model-based Tracker

Participants: Souriya Trinh, Fabien Spindler, Eric Marchand, François Chaumette.

We have extended our model-based visual tracking method by considering as new potential measurement the depth map provided by a RGB-D sensor [75]. The method has been adapted to be fully modular and can combine edge, texture, and depth features. It has been released in the new version of ViSP.

7.1.4. Reflectance and Illumination Estimation for Realistic Augmented Reality

Participants: Salma Jiddi, Eric Marchand.

Photometric registration consists in blending real and virtual scenes in a visually coherent way. To achieve this goal, both reflectance and illumination properties must be estimated. These estimates are then used, within a rendering pipeline, to virtually simulate the real lighting interaction with the scene.

We have been interested in indoor scenes where light bounces off of objects with different reflective properties (diffuse and/or specular). In these scenarios, existing solutions often assume distant lighting or limit the analysis to a single specular object [63]. We address scenes with various objects captured by a moving RGB-D camera and estimate the 3D position of light sources. Furthermore, using spatio-temporal data, our algorithm recovers dense diffuse and specular reflectance maps. Finally, using our estimates, we demonstrate photo-realistic augmentations of real scenes (virtual shadows, specular occlusions) as well as virtual specular reflections on real world surfaces.

We also consider the problem of estimating the 3D position and intensity of multiple light sources using an approach based on cast shadows on textured real surfaces [62], [86]. We separate albedo/texture and illumination using lightness ratios between pairs of points with the same reflectance property but subject to different lighting conditions. Our selection algorithm is robust in presence of challenging textured surfaces. Then, estimated illumination ratios are integrated, at each frame, within an iterative process to recover position and intensity of light sources responsible of cast shadows.

7.1.5. *Multi-Layered Image Representation for Robust SLAM*

Participant: Eric Marchand.

Robustness of indirect SLAM techniques to light changing conditions remains a central issue in the robotics community. With the change in the illumination of a scene, feature points are either not extracted properly due to low contrasts, or not matched due to large differences in descriptors. We proposed a multi-layered image representation (MLI) that computes and stores different contrast-enhanced versions of an original image [76]. Keypoint detection is performed on each layer, yielding better robustness to light changes. An optimization technique is also proposed to compute the best contrast enhancements to apply in each layer in order to improve detection and matching. We extend the MLI approach [77] and we show how Mutual Information can be used to compute dynamic contrast enhancements on each layer. We demonstrate how this approach dramatically improves the robustness in dynamic light changing conditions on both synthetic and real environments compared to default ORB-SLAM. This work focuses on the specific case of SLAM relocation in which a first pass on a reference video constructs a map, and a second pass with a light changed condition relocates the camera in the map.

7.1.6. *Trajectory Generation for Optimal State Estimation*

Participants: Marco Cagnetti, Marco Ferro, Paolo Robuffo Giordano.

This activity addresses the general problem of *active sensing* where the goal is to analyze and synthesize optimal trajectories for a robotic system that can maximize the amount of information gathered by the (few) noisy outputs (i.e., sensor readings) while at the same time reducing the negative effects of the process/actuation noise. Indeed, the latter is far from being negligible for several robotic applications (a prominent example are aerial vehicles). Last year we developed a general framework for solving *online* the active sensing problem by continuously replanning an optimal trajectory that maximize a suitable norm of the Constructibility Gramian (CG), while also coping with a number of constraints including limited energy and feasibility. This approach, however, did not consider the presence of process noise which, as explained, can have a significant effect in many robotic systems of interest (e.g., UAVs). This year we have then extended this work to the case of a non-negligible process noise in [56], where we showed how to generate optimal trajectories able to still maximize the amount of information collected while moving, but by properly weighting (and attenuating) the negative effects of process noise in the execution of the planned trajectory. We are actually working towards the extension of this machinery to the case of realization of a robot task (e.g., reaching and grasping for a mobile manipulators), and to the mutual localization problem for a multi-robot group.

7.1.7. *Cooperative Localization using Interval Analysis*

Participants: Ide Flore Kenmogne Fokam, Vincent Drevelle, Eric Marchand.

In the context of multi-robot fleets, cooperative localization consists in gaining better position estimate through measurements and data exchange with neighboring robots. Positioning integrity (i.e., providing reliable position uncertainty information) is also a key point for mission-critical tasks, like collision avoidance. The goal of this work is to compute position uncertainty volumes for each robot of the fleet, using a decentralized method (i.e., using only local communication with the neighbors). The problem is addressed in a bounded-error framework, with interval analysis and constraint propagation methods. These methods enable to provide guaranteed position error bounds, assuming bounded-error measurements. They are not affected by over-convergence due to data incest, which makes them a well sound framework for decentralized estimation. Uncertainty in the landmarks positions have to be considered, but this can lead to pessimism in the computed solution. Hence we derived a quantifier-free expression of the pose solution-set to improve the vision-based

position domain computation [66]. Image and range based cooperative localization of UAVs has been studied, first in the case of two robots sharing their measurements [65]. Then, scaling to the case of multiple robots as also been addressed, by sharing the computed position domains [64], [67].

7.2. Advanced Sensor-Based Control

7.2.1. Model Predictive Control for Visual Servoing of a UAV

Participants: Bryan Penin, François Chaumette, Paolo Robuffo Giordano.

Visual servoing is a well-known class of techniques meant to control the pose of a robot from visual input by considering an error function directly defined in the image (sensor) space. These techniques are particularly appealing since they do not require, in general, a full state reconstruction, thus granting more robustness and lower computational loads. However, because of the quadrotor underactuation and inherent sensor limitations (mainly limited camera field of view), extending the classical visual servoing framework to the quadrotor flight control is not straightforward. For instance, for realizing a horizontal displacement the quadrotor needs to tilt in the desired direction. This tilting, however, will cause any downlooking camera to point in the opposite direction with, e.g., possible loss of feature tracking because of the limited camera field of view.

In order to cope with these difficulties and achieve a high-performance visual servoing of quadrotor UAVs, we have developed a series of online trajectory re-planning (MPC-like) schemes for explicitly dealing with this kind of constraints during flight. In particular, in [33], the problem of aggressive flight when tracking a target has been considered, with the additional (and complex) constraint of avoiding occlusions w.r.t. obstacles in the scene. A suitable optimization framework has been devised to be solved online during flight for continuously replanning the future UAV trajectory subject to the mentioned sensing constraints as well as actuation constraints. An experimental validation with the quadrotor UAVs available in the team has also been provided. In [34], we have instead considered the problem of planning a trajectory from a start to a goal location for a UAV equipped with an onboard camera, by assuming that measurements of environment landmarks (needed to recover the UAV state from visual input) may be intermittent due to occlusions by obstacles. The goal is then to plan a trajectory that can minimize the negative effects of “missing measurements” by keeping the state uncertainty limited despite the temporary loss of measurements. This planning problems has been solved by exploiting a bi-directional RRT algorithm for joining the start and goal locations, and an experimental validation has also been performed.

7.2.2. UAVs in Physical Interaction with the Environment

Participants: Quentin Delamare, Paolo Robuffo Giordano.

Most research in UAVs deals with either contact-free cases (the UAVs must avoid any contact with the environment), or “static” contact cases (the UAVs need to exert some forces on the environment in quasi-static conditions, reminiscent of what has been done with manipulator arms). Inspired by the vast literature on robot locomotion (from, e.g., the humanoid community), in this research topic we aim at exploiting the contact with the environment for helping a UAV maneuvering in the environment, in the same spirit in which we humans (and, supposedly, humanoid robots) use our legs and arms when navigating in cluttered environments for helping in keeping balance, or perform maneuvers that would be, otherwise, impossible. During last year we have considered in [17] the modeling, control and trajectory planning problem for a planar UAV equipped with a 1 DoF actuated arm capable of hooking at some pivots in the environment. This UAV (named MonkeyRotor) needs to “jump” from one pivot to the next one by exploiting the forces exchanged with the environment (the pivot) and its own actuation system (the propellers), see Fig. 9(a). We are currently finalizing a real prototype (Fig. 9(b)) for obtaining an experimental validation of the whole approach.

7.2.3. Trajectory Generation for Minimum Closed-Loop State Sensitivity

Participants: Quentin Delamare, Paolo Robuffo Giordano.

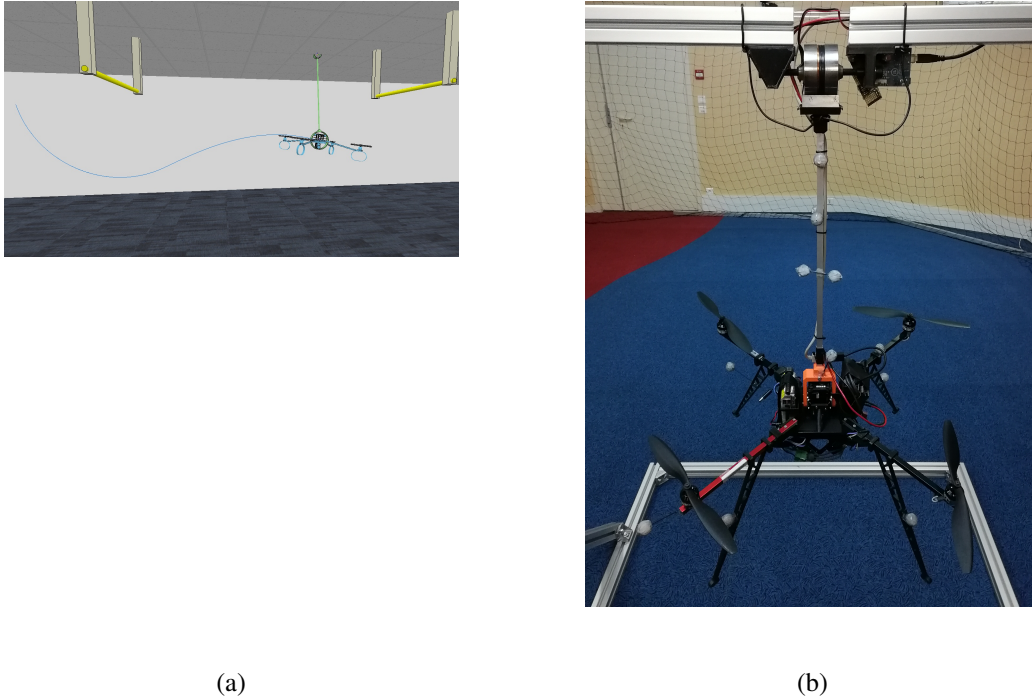


Figure 9. UAVs in Physical Interaction with the Environment. a) The simulated MonkeyRotor performing a hook-to-hook maneuver. b) The prototype currently under finalization.

The goal of this research activity is to propose a new point of view in addressing the control of robots under parametric uncertainties: rather than striving to design a sophisticated controller with some robustness guarantees for a specific system, we propose to attain robustness (for any choice of the control action) by suitably shaping the reference motion trajectory so as to minimize the *state sensitivity* to parameter uncertainty of the resulting closed-loop system. In [70], we have explored this novel idea by showing how to properly define and evaluate the *state sensitivity matrix* and its gradient w.r.t. the desired trajectory parameters. This then allows setting up an optimization problem in which the desired trajectory is optimized so as to minimize a suitable norm of the state sensitivity. The machinery has been applied to two case studies involving a unicycle and a planar quadrotor with successful results (monte-carlo statistical analysis). We are currently considering extensions of this initial idea (e.g., by also considering a notion of *input sensitivity*), as well as an experimental validation of the approach.

7.2.4. Visual Servoing for Steering Simulation Agents

Participants: Axel Lopez Gandia, Eric Marchand, François Chaumette, Julien Pettré.

This research activity is dedicated to the simulation of human locomotion, and more especially to the simulation of the visuomotor loop that controls human locomotion in interaction with the static and moving obstacles of its environment. Our approach is based on the principles of visual servoing for robots. To simulate visual perception, an agent perceives its environment through a virtual camera located the position of its head. The visual input is processed by each agent in order to extract the relevant information for controlling its motion. In particular, the optical flow is computed to give the agent access to the relative motion of visible objects around it. Some features of the optical flow are finally extracted to estimate the risk of collision with obstacle. We have established the mathematical relations between those visual features and the agent's self motion. Therefore, when necessary, the agent motion is controlled and adjusted so as to cancel the visual

features indicating a risk of future collision. We are now in the process of evaluating our motion control technique and exploring relevant applications, as well as preparing a publication summarizing this work.

7.2.5. *Study of human locomotion to improve robot navigation*

Participants: Florian Berton, Julien Bruneau, Julien Pettré.

This research activity is dedicated to the study of human gaze behaviour during locomotion. This activity is directly linked to the previous one on simulation, as human locomotion study results will serve as an input for the design of novel models for simulation. In this activity, we are first interested in collective pedestrian dynamics, i.e., how humans move in crowds, how they interact locally and how this results into the emergence of specific patterns at larger scales [52]. Virtual Reality is one main experimental tools in our approach, so as to control and reproduce easily situations we expose participants to, as well as to explore the nature of the visual cues human use to control their locomotion [22], [68]. We are also interested in the study of the activity of the gaze during locomotion that, in addition to the classical study of kinematics motion parameters, provides information on the nature of visual information acquired by humans to move, and the relative importance of visual elements in their surroundings [54], [26]. We directly exploit our experimental result to propose relevant navigation control techniques for robot to make them more adapted to move among humans [41], [58].

7.2.6. *Direct Visual Servoing*

Participants: Quentin Bateux, Eric Marchand.

We proposed a deep neural network-based method to perform high-precision, robust and real-time 6 DOF positioning tasks by visual servoing [53]. A convolutional neural network is fine-tuned to estimate the relative pose between the current and desired images and a pose-based visual servoing control law is considered to reach the desired pose. This approach efficiently and automatically creates a dataset used to train the network. We show that this enables the robust handling of various perturbations (occlusions and lighting variations). We then propose the training of a scene-agnostic network by providing both the desired and current images to a deep network for generating the camera motion. The method is validated on a 6 DOF robot.

7.2.7. *Visual Servoing using Wavelet and Shearlet Transforms*

Participants: Lesley-Ann Dufлот, Alexandre Krupa.

We pursued our work on the elaboration of a direct visual servoing method in which the signal control inputs are the coefficients of a multiscale image representation [4]. In particular, we considered the use of multiscale image representations that are based on discrete wavelet and shearlet transforms. This year, we succeeded to derive an analytical formulation of the interaction matrix related to the wavelet and shearlet coefficients and experimentally demonstrated the performances of the proposed visual servoing approaches [18]. We also considered this control framework in a medical application which consists in automatically moving a biological sample carried by a parallel micro-robotic platform using Optical Coherence Tomography (OCT) as visual feedback. The objective of this application was to automatically retrieve the region of the sample that corresponds to an initial optical biopsy for diagnosis purpose. Experimental results demonstrated the efficiency of our approach that uses the wavelet coefficients of the OCT image as input of the control law to perform this task [61].

7.2.8. *Visual Servoing from the Trifocal Tensor*

Participants: Kaixiang Zhang, François Chaumette.

In visual servoing, three images are usually available at each iteration of the control loop: the very first one, the current one, and the desired one. That is why the trifocal tensor defined from this set of images is a potential candidate for providing visual features to be used as inputs of the control scheme. We have first modeled the interaction matrix related to the components of the trifocal tensor. We have then designed a set of reduced visual features with good decoupling properties, from which a thorough Lyapunov-based stability analysis has been developed [78].

7.2.9. 3D Steering of Flexible Needle by Ultrasound Visual Servoing

Participants: Jason Chevie, Marie Babel, Alexandre Krupa.

Needle insertion procedures under ultrasound guidance are commonly used for diagnosis and therapy. However, it is often critical to accurately reach a targeted region due to the deflection of the flexible needle and the presence of intra-operative tissue motions. Therefore this year we improved our robotic framework dedicated to 3D steering of flexible needle that is based on ultrasound visual servoing. We developed a new control approach that both steers the flexible needle toward a desired target and compensates the tissue self-motion during the needle insertion. In our approach, the target to be reached by the needle is tracked in 2D ultrasound images and the needle tip position and orientation are measured by an electromagnetic tracker. Tissue motion compensation is performed using force feedback to reduce targeting error and forces applied to the tissue. The method also uses a mechanics-based interaction model that is updated online to provide the current shape of the deformable needle. In addition, a novel control law using task functions was proposed to fuse motion compensation, needle steering via manipulation of its base and steering of the needle tip in order to reach the target. Validation of the tracking and steering algorithms were performed in gelatin phantom and bovine liver on which periodical perturbation motions (magnitude of 15 mm) were applied to simulate physiological motions. Experimental results demonstrated that our approach can reach a moving target with an average targeting error of 1.2 mm and 2.5 mm in resp. gelatin and liver, which is accurate enough for common needle insertion procedures [12].

7.2.10. Robotic Assistance for Ultrasound Elastography by Visual Servoing, Force Control and Teleoperation

Participants: Pedro Alfonso Patlan Rosales, Alexandre Krupa.

Ultrasound elastography is an image modality that unveils elastic parameters of a tissue, which are commonly related with certain pathologies. It is performed by applying continuous stress variation on the tissue in order to estimate a strain map from successive ultrasound images. Usually, this stress variation is performed manually by the user through the manipulation of an ultrasound probe and it results therefore in a user-dependent quality of the strain map. To improve the ultrasound elastography imaging and provide quantitative measurements, we developed an assistant robotic palpation system that automatically applies the motion to a 2D or 3D ultrasound probe that is needed to generate in real-time the elastography images during teleoperation [5]. This year, we have extended our robotic framework by developing a method that provides to the user the capability to physically feel the stiffness of the observed tissue of interest via a haptic device. This work has been submitted to the ICRA 2019 conference.

7.2.11. Deformation Servoing of Soft Objects

Participant: Alexandre Krupa.

This year, we started a new research activity whose objective is to provide robotic control approaches that improve the dexterity of robots interacting with deformable objects. The goal is to control one or several robots interacting with a soft object in such a way to reach a desired configuration of object deformation. Nowadays, most of the existing deformation control methods require accurate models of the object and/or environment in order to perform such tasks. Contrarily to these methods, we want to propose model-free methods that rely only on visual observation provided by a RGB-D sensor to control the deformation of soft objects without a priori knowledge of their material mechanical parameters and without a priori knowledge of their environment. In a preliminary study, we compared the model-based method based on physics simulation (Finite Element Model) and the model-free method of the state of the art. We also developed a first approach based on visual servoing that uses in the robot control law an online estimation of the interaction matrix that links the variation of the object deformation to the velocity of the robot end-effector. These different approaches have been implemented in simulation and are currently tested on a robotic arm (Adept Viper 650) interacting with a soft object (sponge). The first results are encouraging since they showed that our model-free visual servoing approach based on online estimation of the interaction matrix provides similar results than the model-based approach based on physics simulation.

7.2.12. Multi-Robot Formation Control

Participants: Paolo Robuffo Giordano, Fabrizio Schiano.

Most multi-robot applications must rely on relative sensing among the robot pairs (rather than absolute/external sensing such as, e.g., GPS). For these systems, the concept of rigidity provides the correct framework for defining an appropriate sensing and communication topology architecture. In our previous works we have addressed the problem of coordinating a team of quadrotor UAVs equipped with onboard cameras from which one could extract “relative bearings” (unit vectors in 3D) w.r.t. the neighboring UAVs in visibility. This problem is known as bearing-based formation control and localization. In [71], we considered the localization problem for multi-robots (that is, the problem of reconstructing the relative poses from the available bearing measurements), by recasting it as a nonlinear observability problem: this rigorous analysis led us to introduce the notion of *Dynamic Bearing Observability Matrix*, which in a sense extends the classical Bearing Rigidity Matrix to explicitly account for the robot motion. It was then possible to show that the scale factor of the formation is, indeed, observable by processing the bearing measurements and (known) agent motion, a result confirmed experimentally by employing a EKF on a group of quadrotor UAVs. This and more results on bearing-based formation control and localization for quadrotor UAVs are summarized in [7].

7.2.13. Coupling Force and Vision for Controlling Robot Manipulators

Participants: François Chaumette, Paolo Robuffo Giordano, Alexander Oliva.

The goal of this recent activity is about coupling visual and force information for advanced manipulation tasks. To this end, we plan to exploit the recently acquired Panda robot (see Sect. 6.6.4), a state-of-the-art 7-dof manipulator arm with torque sensing in the joints, and the possibility to command torques at the joints or forces at the end-effector. Thanks to this new robot, we plan to study how to optimally combine the torque sensing and control strategies that have been developed over the years to also include in the loop the feedback from a vision sensor (a camera). In fact, the use of vision in torque-controlled robot is quite limited because of many issues, among which the difficulty of fusing low-rate images (about 30 Hz) with high-rate torque commands (about 1 kHz), the delays caused by any image processing and tracking algorithms, and the unavoidable occlusions that arise when the end-effector needs to approach an object to be grasped. Our aim is therefore to advance the state-of-the-art in the field of torque-controlled manipulator arms by also including in the loop in an explicit way the use of a vision sensor. We will probably rely on estimation strategies for coping with the different rates of the two sensing modalities, and to online trajectory replanning strategies for dealing with constraints of the system (e.g., limited fov of the camera, of the fact that visibility of the target object is lost when closing in for grasping).

7.3. Haptic Cueing for Robotic Applications

7.3.1. Haptic Guidance of a Biopsy Needle

Participants: Hadrien Gurnel, Alexandre Krupa.

The objective of this work is to provide assistance during manual needle steering for biopsies or therapy purposes (see Section 9.1.6). At the difference of our work presented in Section 7.2.9 where a robotic system is used to autonomously actuate the needle, we propose in this study another way of assistance for needle insertion. The principle is to provide haptic cue feedback to the clinician in order to help him during his manual gesture by the application of repulsive or attractive forces. The proposed solution is based on a shared robotic control, where the clinician and a haptic device, both holding the base of the needle, cooperate together. In a preliminary study, we elaborated 5 different haptic-guidance strategies to assist the needle pre-positioning and pre-orienting on a pre-defined insertion point, and with a pre-planned desired incidence angle. From this pre-operative information and intra-operative measurements of the location of the needle, haptic cues are generated to guide the clinician toward the desired needle position and orientation. These 5 different haptic guides were recently tested by 2 physicians, both experts in needle manipulation and compared to the reference gesture performed without assistance. The results have been submitted to the IPCAI 2019 conference. Future work will consist in evaluating the different haptic guides from an user-experience study involving more participants.

7.3.2. Wearable Haptics

Participants: Marco Aggravi, Claudio Pacchierotti, Paolo Robuffo Giordano.

We worked on a wearable haptic device for the forearm and its application in robotic teleoperation [8]. The device is able to provide skin stretch, pressure, and vibrotactile stimuli, see Fig. 10. Two servo motors, housed in a 3D printed lightweight platform, actuate an elastic fabric belt, wrapped around the arm. When the two servo motors rotate in opposite directions, the belt is tightened (or loosened), thereby compressing (or decompressing) the arm. On the other hand, when the two motors rotate in the same direction, the belt applies a shear force to the arm skin. Moreover, the belt houses four vibrotactile motors, positioned evenly around the arm at 90 degrees from each other. The device weighs 220 g for $115 \times 122 \times 50$ mm of dimensions, making it wearable and unobtrusive. We carried out a perceptual characterization of the device as well as two human-subjects teleoperation experiments in a virtual environment, employing a total of 34 subjects.

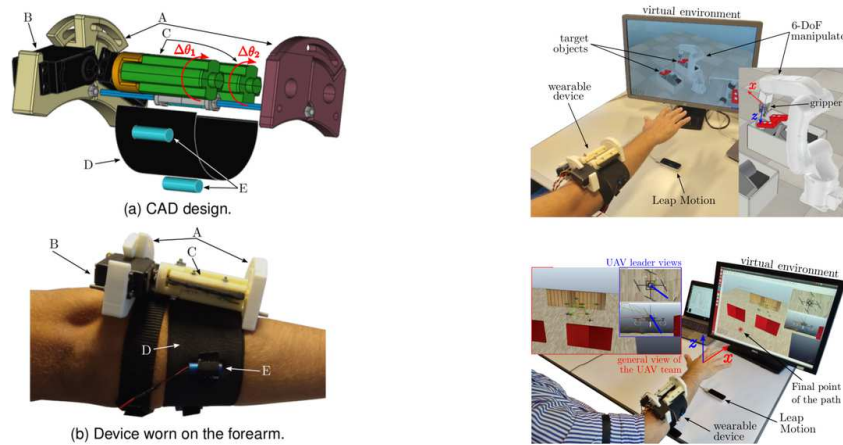


Figure 10. The proposed wearable device for the arm and its evaluation. The device consists of a static platform (A) that accommodates two servomotors (B) and two pulleys (C), a fabric belt (D), and four vibrotactile motors (E).

In the first experiment, participants were asked to control the motion of a robotic manipulator for grasping an object; in the second experiment, participants were asked to teleoperate the motion of a quadrotor fleet along a given path. In both scenarios, the wearable haptic device provided feedback information about the status of the slave robot(s) and of the given task. Results showed the effectiveness of the proposed device. Performance on completion time, length trajectory, and perceived effectiveness when using the wearable device improved of 19.8%, 25.1%, and 149.1% than when wearing no device, respectively. Finally, all subjects but three preferred the conditions including wearable haptics.

7.3.3. Mid-Air Haptic Feedback

Participants: Claudio Pacchierotti, Thomas Howard.

GUIs have been the gold standard for more than 25 years. However, they only support interaction with digital information indirectly (typically using a mouse or pen) and input and output are always separated. Furthermore, GUIs do not leverage our innate human abilities to manipulate and reason with 3D objects. Recently, 3D interfaces and VR headsets use physical objects as surrogates for tangible information, offering limited malleability and haptic feedback (e.g., rumble effects). In the framework of project H-Reality, we are working to develop novel mid-air haptics paradigm that can convey the information spectrum of touch

sensations in the real world, motivating the need to develop new, natural interaction techniques. Moreover, we want to use robotic manipulators to enlarge the workspace of mid-air haptic systems, using depth cameras and visual servoing techniques to follow the motion of the user's hand.

7.3.4. Haptic Cueing in Telemanipulation

Participants: Firas Abi Farraj, Paolo Robuffo Giordano, Claudio Pacchierotti.

Robotic telemanipulators are already widely used in nuclear decommissioning sites for handling radioactive waste. However, currently employed systems are still extremely primitive, making the handling of these materials prohibitively slow and ineffective. As the estimated cost for the decommissioning and clean-up of nuclear sites keeps rising, it is clear that one would need faster and more effective approaches. Towards this goal, we presented the user evaluation of a recently proposed haptic-enabled shared-control architecture for telemanipulation [51]. An autonomous algorithm regulates a subset of the slave manipulator degrees of freedom (DoF) in order to help the human operator in grasping an object of interest. The human operator can then steer the manipulator along the remaining null-space directions with respect to the main task by acting on a grounded haptic interface. The haptic cues provided to the operator are designed in order to inform about the feasibility of the user's commands with respect to possible constraints of the robotic system. This work compared this shared-control architecture against a classical 6-DOF teleoperation approach in a real scenario by running experiments with 10 subjects. The results clearly show that the proposed shared-control approach is a viable and effective solution for improving currently-available teleoperation systems in remote telemanipulation tasks.

7.3.5. Haptic Feedback for an Augmented Wheelchair Driving Experience

Participants: Louise Devigne, Marie Babel, François Pasteau.

Smart powered wheelchairs can increase mobility and independence for people with disability by providing navigation support. For rehabilitation or learning purposes, it would be of great benefit for wheelchair users to have a better understanding of the surrounding environment while driving. Therefore, a way of providing navigation support is to communicate information through a dedicated and adapted feedback interface. We have then proposed a framework in which feedback is provided by sending forces through the wheelchair controller as the user steers the wheelchair. This solution is based on a low complex optimization framework able to perform smooth trajectory correction and to provide obstacle avoidance. The impact of the proposed haptic guidance solution on user driving performance was assessed during this pilot study for validation purposes through an experiment with 4 able-bodied participants. Results of this pilot study showed that the number of collisions significantly decreased while force feedback was activated, thus validating the proposed framework [60].

7.3.6. Virtual Shadows to Improve Self Perception in CAVE

Participants: Guillaume Cortes [Hybrid], Eric Marchand.

In immersive projection systems (IPS), the presence of the user's real body limits the possibility to elicit a virtual body ownership illusion. But, is it still possible to embody someone else in an IPS even though the users are aware of their real body ? In order to study this question, we propose to consider using a virtual shadow in the IPS, which can be similar or different from the real user's morphology. We have conducted an experiment ($N = 27$) to study the users' sense of embodiment whenever a virtual shadow was or was not present. Participants had to perform a 3D positioning task in which accuracy was the main requirement. The results showed that users widely accepted their virtual shadow (agency and ownership) and felt more comfortable when interacting with it (compare to no virtual shadow). Yet, due to the awareness of their real body, the users have less acceptance of the virtual shadow whenever the shadow gender differs from their own. Furthermore, the results showed that virtual shadows increase the users' spatial perception of the virtual environment by decreasing the inter-penetrations between the user and the virtual objects. Taken together, our results promote the use of dynamic and realistic virtual shadows in IPS and pave the way for further studies on "virtual shadow ownership" illusion.

7.4. Shared Control Architectures

7.4.1. Shared Control for Remote Manipulation

Participants: Firas Abi Farraj, Paolo Robuffo Giordano, Claudio Pacchierotti, Rahaf Rahal, Mario Selvaggio.

As teleoperation systems become more sophisticated and flexible, the environments and applications where they can be employed become less structured and predictable. This desirable evolution toward more challenging robotic tasks requires an increasing degree of training, skills, and concentration from the human operator. For this reason, researchers started to devise innovative approaches to make the control of such systems more effective and intuitive. In this respect, shared control algorithms have been investigated as one of the main tools to design complex but intuitive robotic teleoperation systems, helping operators in carrying out several increasingly difficult robotic applications, such as assisted vehicle navigation, surgical robotics, brain-computer interface manipulation, rehabilitation. This approach makes it possible to share the available degrees of freedom of the robotic system between the operator and an autonomous controller. The human operator is in charge of imparting high level, intuitive goals to the robotic system; while the autonomous controller translates them into inputs the robotic system can understand. How to implement such division of roles between the human operator and the autonomous controller highly depends on the task, robotic system, and application. Haptic feedback and guidance have been shown to play a significant and promising role in shared control applications. For example, haptic cues can provide the user with information about what the autonomous controller is doing or is planning to do; or haptic force can be used to gradually limit the degrees of freedom available to the human operator, according to the difficulty of the task or the experience of the user. The dynamic nature of haptic guidance enables us to design very flexible robotic systems, which can easily and rapidly change the division of roles between the user and autonomous controller.

Along this general line of research, we worked at different approaches:

- We proposed novel haptic guidance methods for a dual-arm telerobotic manipulation system [36] which are able to deal with several different constraints, such as collisions, joint limits, and singularities. We combined the haptic guidance with shared-control algorithms for autonomous orientation control and collision avoidance meant to further simplify the execution of grasping tasks. In addition, a human subject study was carried out to assess the effectiveness and applicability of the proposed control approaches both in simulated and real scenarios. Results showed that the proposed haptic-enabled shared-control methods significantly improve the performance of grasping tasks with respect to the use of classic teleoperation with neither haptic guidance nor shared control. Live demos of some of these approaches have been shown to the general public at the Maker Faire 2018 in Rome.
- In the framework of the RoMANS H2020 project, we worked together with CEA to implement an intuitive and effective shared-control teleoperation system with haptic feedback using the CEA robotic hand at the slave side and the Haption glove at the master side. The system was tested at CEA in an object grasping, manipulation, and sorting scenario. A video of the experiment is available at: <https://youtu.be/M-tpVP9Fakc>.
- Finally, in [38] we reported the results of a collaborative project involving LAAS-CNRS as leader, where we implemented an aerial-ground comanipulator system, denoted *Tele-MAGMaS*, where a fixed-based manipulator arm cooperates with a UAV equipped with an onboard gripper for carrying together (and manipulating) a long bar. The system has been demonstrated live during the Hannover Fair in 2017.

7.4.2. Shared Control for Mobile Robot Navigation

Participant: Paolo Robuffo Giordano.

Besides manipulators, we also considered shared control algorithms for mobile robot navigation. In [25], we have presented (and experimentally validated) an online trajectory planning approach that allows a human operator to act on the trajectory to be tracked by a mobile robot (a quadrotor UAV in the experiments) in conjunction with the robot autonomy which can locally modify the planned trajectory for avoiding obstacles of staying close to points of interest. This “shared planning approach” is quite general and its application to other robotic systems is under investigation.

7.4.3. Shared Control of a Wheelchair for Navigation Assistance

Participants: Louise Devigne, Marie Babel.

Power wheelchairs allow people with motor disabilities to have more mobility and independence. However, driving safely such a vehicle is a daily challenge particularly in urban environments while encountering *negative* obstacles, dealing with uneven grounds, etc. Indeed, differences of elevation have been reported to be one of the most challenging environmental barrier to negotiate while driving a wheelchair with tipping and falling being is the most common accidents power wheelchair users encounter. It is thus our actual challenge to design assistive solutions for power wheelchair navigation in order to improve safety while navigating in such environments. To this aim, we proposed a first shared-control algorithm which provides assistance while navigating with a wheelchair in an environment consisting of negative obstacles [80].

7.4.4. Wheelchair Kinematics and Dynamics Modeling for Shared Control

Participants: Aline Baudry, Marie Babel.

The driving experience of an electric powered wheelchair can be disturbed by the dynamic and kinematic effects of the passive caster wheels, particularly during maneuvers in narrow rooms and direction changes. In order to prevent their nasty behaviour, we proposed a caster wheel behavior model based on experimental measurements. The study has been realised for the three existing types of wheelchair, which present different kinematic behaviors, i.e. front caster type, rear caster type and mid-wheel drive. The orientation of the caster wheels has been measured experimentally for different initial orientations, velocities and user mass, according to a predefined experimental design. The repeatability of the motions has been studied, and from these measurements, their behavior has been modeled. By using this model with the wheelchair kinematic expressions, we were able to calculate the real trajectory of the wheelchair to enhance an existing driving assistance for powered wheelchair [79].

7.4.5. Wheelchair Autonomous Navigation for Fall Prevention

Participants: Solenne Fortun, Marie Babel.

The Prisme project (see Section 9.1.7) is devoted to fall prevention and detection of inpatients with disabilities. For wheelchair users, falls typically occur during transfer between the bed and the wheelchair and are mainly due to a bad positioning of the wheelchair. In this context, the Prisme project addresses both fall prevention and detection issues by means of a collaborative sensing framework. Ultrasonic sensors are embedded onto both a robotized wheelchair and a medical bed. The measured signals are used to detect fall and to automatically drive the wheelchair near the bed at an optimal position determined by occupational therapists. This year, we designed the related control framework based on sensor-based servoing principles and validated it in simulation. Next step will consist in realizing tests within the Rehabilitation Center of Pôle Saint Héliar.

7.4.6. Robot-Human Interactions during Locomotion

Participants: Julien Legros, Javad Amirian, Fabien Grzeskowiak, Ceilidh Hoffmann, Marie Babel, Jean Bernard Hayet, Julien Pettré.

This research activity is dedicated to the design of robot navigation techniques to make them capable of safely moving through a crowd of people. We are following two main research paths. The first one is dedicated to the prediction of crowd motion based on the state of the crowd as sensed by a robot. The second one is dedicated to the creation of a virtual reality platform that enables robots and humans to share a common virtual space where robot control techniques can be tested with no physical risk of harming people, as they remain separated in the physical space. We are currently developing these ideas, which should bring good results in the near future.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Robocortex

Participants: Fabien Spindler, François Chaumette.

no Inria Rennes 11369, duration: 20 months.

This contract with the Inria Robocortex start up in Sophia-Antipolis ended in May 2018. It is devoted to provide our expertise in visual tracking for an application specified by Dassault Aviation.

8.1.2. ABB

Participants: Souriya Trinh, Fabien Spindler, François Chaumette.

no Inria Rennes 12597, duration: 8 months.

This contract with ABB in Barcelona started in September 2017. It is devoted to provide our expertise in visual tracking and visual servoing for an industrial application.

8.1.3. IRT b<>com

Participants: Hadrien Gurnel, Fabien Spindler, Alexandre Krupa.

no Inria Rennes 11774, duration: 36 months.

This contract started in October 2016 and concerns the leasing to IRT b<>com of two modules of the Rainbow medical robotic platform. Each module is rent 40 days during a 3-year period in the context of the IRT b<>com NeedleWare project (see Section 9.1.6).

8.2. Bilateral Grants with Industry

8.2.1. Pôle Saint Hélier

Participants: Louise Devigne, Marie Babel.

no Insa Rennes 2015/0890, duration: 36 months.

This project started in November 2015 and supports Louise Devigne PhD about wheelchair navigation assistance. The idea is first to design a low-cost indoor / outdoor efficient obstacle avoidance system that respects the user intention, and does not alter user perception. The second objective is to take advantage of the proposed assistive tool to enhance the user Quality of Experience by means of biofeedback as well as the understanding of the evolution of the pathology.

8.2.2. Technicolor

Participants: Salma Jiddi, Eric Marchand.

no Univ. Rennes 1 15CC310-02D, duration: 36 months.

This project funded by Technicolor started in October 2015. It supports Salma Jiddi's Ph.D. about augmented reality (see Section 7.1.4).

8.2.3. Realyz

Participant: Eric Marchand.

no Inria Rennes 10822, duration: 36 months.

This project funded by Realyz started in October 2015. It is achieved in cooperation with Anatole Lécuyer from Hybrid group at Irisa and Inria Rennes-Bretagne Atlantique to support Guillaume Cortes Ph.D. about motion tracking in virtual reality.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. *ARED Locoflot*

Participants: Ide Flore Kenmogne Fokam, Vincent Drevelle, Eric Marchand.

no Inria Rennes 9944, duration: 36 months.

This project funded by the Brittany council started in October 2015. It supports in part Ide Flore Kenmogne Fokam's Ph.D. about cooperative localization in multi-robot fleets using interval analysis (see Section 7.1.7).

9.1.2. *ARED Mod4Nav*

Participants: Aline Baudry, Marie Babel.

no INSA Rennes 2016/01, duration: 36 months.

This project funded by the Brittany council started in October 2016. It supports in part Aline Baudry's Ph.D. about wheelchair modeling.

9.1.3. *Allocation d'installation scientifique*

Participant: Claudio Pacchierotti.

no CNRS Rennes 17C0487, duration: 36 months.

This grant from "Rennes Métropole" has been obtained in July 2017 and supported the activities related to the teleoperation of drones (quadrotor UAVs) using wearable haptics interfaces.

9.1.4. *IRT Jules Verne Mascot*

Participants: François Chaumette, Fabien Spindler, Souriya Trinh.

no Inria Rennes 10361, duration: 36 months.

This project ended in December 2018. It was managed by IRT Jules Verne in Nantes and achieved in cooperation with LS2N, Airbus, Renault, Faurecia and GE. Our goal in this project was to perform screwing for various industrial applications by visual servoing. We also developed an application of rivet detection and 3D localisation on an aircraft cabin.

9.1.5. *IRT Jules Verne Happy*

Participant: François Chaumette.

no Inria Rennes 13521, duration: 36 months.

This project started in June 2018. It is managed by IRT Jules Verne in Nantes and achieved in cooperation with LS2N and Airbus. Its goal is to develop local sensor-based control methods for the assembly of large parts of aircrafts.

9.1.6. *IRT b<>com NeedleWare*

Participants: Hadrien Gurnel, Alexandre Krupa.

no Inria Rennes 9072, duration: 36 months.

This project started in October 2016. It supports Hadrien Gurnel's Ph.D. about the study of a shared control strategy fusing haptic and visual control for assisting manual steering of needles for biopsy or therapy purposes in a synergetic way (see Section 7.3.1).

9.1.7. *Prisme*

Participants: Solenne Fortun, Marie Babel.

no Insa Rennes 2017-0004, duration: 33 months.

This project started in January 2017 and is supported by Brittany region/BPI. This project aims at designing a fall prevention strategy based on the sensing collaboration of a smart wheelchair and a smart medical bed. Fall detection and automatic positioning of the wheelchair next to the bed issues are planned to be addressed (see Section 7.4.5).

9.1.8. Silver Connect

Participant: Marie Babel.

no Insa Rennes 2018-0076, duration: 24 months.

This project started in November 2018 and is supported by Brittany region/BPI as well as FEDER. This project aims at designing a fall detection framework by means of vision-based algorithms coupled with deep learning solutions.

9.2. National Initiatives

9.2.1. ANR JCJC SenseFly

Participants: Muhammad Usman, Paolo Robuffo Giordano.

no Iria CNRS 50476, duration: 36 months.

The ANR “Jeune Chercheur” SenseFly project started in August 2015 and ended in December 2018. Its goal is to advance the state-of-the-art in multi-UAV in the design and implementation of fully decentralized and sensor-based group behaviors by only resorting to onboard sensing (mainly cameras and IMU) and local communication (e.g., Bluetooth communication, wireless networks). Topics such as individual flight control, formation control robust against sensor limitations (e.g., limited field of view, occlusions), distributed estimation of relative positions/bearings from local sensing, maintenance of architectural properties of a multi-UAV formation are studied in the project. Part of the platforms described in Section 6.6.6 has been purchased thanks to this grant.

9.2.2. ANR PLaTINUM

Participant: Vincent Drevelle.

no Inria Sophia 10204, duration: 42 months.

This project started in November 2015. It involves a consortium managed by Litis in Rouen with IGN Matis (Paris), Le2i (Le Creusot) and Rainbow group. It aims at proposing novel solutions to robust long-term mapping of urban environments.

9.2.3. Equipex Robotex

Participants: Fabien Spindler, François Chaumette.

no Inria Rennes 6388, duration: 9 years.

Rainbow is one of the 15 French academic partners involved in the Equipex Robotex network that started in February 2011. It is devoted to get and manage significant equipment in the main robotics labs in France. In the scope of this project, we have obtained the humanoid robot Romeo (see Section 6.6.5).

9.2.4. CNRS/INS2I - PEPS JCJC ShareHaptics

Participant: Claudio Pacchierotti.

no Inria Rennes 7991, duration: 12 months.

The project addresses the need of combining wearable haptics and shared control. Shared-control techniques will enable a single user to intuitively control the coordinated motion of several robots (e.g., a team of drones/manipulators). At the same time, multi-type multi-point wearable haptic devices will provide the necessary multi-faceted feedback information to the user.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. FP7 Space RemoveDEBRIS

Participants: Eric Marchand, François Chaumette.

Instrument: Specific Targeted Research Project

Duration: October 2013 - March 2019

Coordinator: University of Surrey (United Kingdom)

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

Inria contact: François Chaumette

Abstract: Our goal in this project is to validate model-based tracking algorithms on images acquired during an actual space debris removal mission [74],[73].

9.3.1.2. H2020 ICT Comanoid

Participants: Souriya Trinh, Fabien Spindler, François Chaumette.

Title: Multi-contact Collaborative Humanoids in Aircraft Manufacturing

Programme: H2020

Duration: January 2015 - December 2018

Coordinator: CNRS (Lirmm)

Partners: Airbus Group (France), DLR (Germany), Università Degli Studi di Roma La Sapienza (Italy), CNRS (I3S)

Inria contact: François Chaumette

Abstract: Comanoid investigates the deployment of robotic solutions in well-identified Airbus airliner assembly operations that are laborious or tedious for human workers and for which access is impossible for wheeled or rail-ported robotic platforms. As a solution to these constraints a humanoid robot is proposed to achieve the described tasks in real-use cases provided by Airbus Group. At a first glance, a humanoid robotic solution appears extremely risky, since the operations to be conducted are in highly constrained aircraft cavities with non-uniform (cargo) structures. Furthermore, these tight spaces are to be shared with human workers. Recent developments, however, in multi-contact planning and control suggest that this is a much more plausible solution than current alternatives such as a manipulator mounted on multi-legged base. Indeed, if humanoid robots can efficiently exploit their surroundings in order to support themselves during motion and manipulation, they can ensure balance and stability, move in non-gaited (acyclic) ways through narrow passages, and also increase operational forces by creating closed-kinematic chains. Bipedal robots are well suited to narrow environments specifically because they are able to perform manipulation using only small support areas. Moreover, the stability benefits of multi-legged robots that have larger support areas are largely lost when the manipulator must be brought close, or even beyond, the support borders. COMANOID aims at assessing clearly how far the state-of-the-art stands from such novel technologies. In particular the project focuses on implementing a real-world humanoid robotics solution using the best of research and innovation. The main challenge are to integrate current scientific and technological advances including multi-contact planning and control; advanced visual-haptic servoing; perception and localization; human-robot safety, and the operational efficiency of cobotics solutions in airliner manufacturing.

This year, we published [75] in the scope of this project (see Section 7.1.3). Short stays have been achieved at DLR and LIRMM for the integration of our visual tracking and visual servoing methods on the humanoid robots Toro and HRP-4.

9.3.1.3. H2020 ICT Romans

Participants: Firas Abi Farraj, Marco Cognetti, Marco Aggravi, Fabrizio Schiano, Pol Mordel, Fabien Spindler, François Chaumette, Claudio Pacchierotti, Paolo Robuffo Giordano.

Title: Robotic Manipulation for Nuclear Sort and Segregation

Programme: H2020

Duration: May 2015 - October 2018

Coordinator: University of Birmingham

Partners: NLL (UK), CEA (France), Univ. Darmstadt (Germany)

CNRS contact: Paolo Robuffo Giordano

Abstract: The goal of the RoMaNS (Robotic Manipulation for Nuclear Sort and Segregation) project has been to advance the state of the art in mixed autonomy for tele-manipulation, to solve a challenging and safety-critical “sort and segregate” industrial problem, driven by urgent market and societal needs. Cleaning up the past half century of nuclear waste, in the UK alone (mostly at the Sellafield site), represents the largest environmental remediation project in the whole of Europe. Most EU countries face related challenges. Nuclear waste must be “sorted and segregated”, so that low-level waste is placed in low-level storage containers, rather than occupying extremely expensive and resource intensive high-level storage containers and facilities. Many older nuclear sites (>60 years in UK) contain large numbers of legacy storage containers, some of which have contents of mixed contamination levels, and sometimes unknown contents. Several million of these legacy waste containers must now be cut open, investigated, and their contents sorted. This can only be done remotely using robots, because of the high levels of radioactive material. Current state-of-the-art practice in the industry, consists of simple tele-operation (e.g. by joystick or teach-pendant). Such an approach is not viable in the long-term, because it is prohibitively slow for processing the vast quantity of material required. The project aimed at: 1) Develop novel hardware and software solutions for advanced bi-lateral master-slave tele-operation. 2) Develop advanced autonomy methods for highly adaptive automatic grasping and manipulation actions. 3) Combine autonomy and tele-operation methods using state-of-the-art understanding of mixed initiative planning, variable autonomy and shared control approaches. 4) Deliver a TRL 6 demonstration in an industrial plant-representative environment at the UK National Nuclear Lab Workington test facility.

9.3.1.4. H2020 ICT CrowdBot

Participants: Julien Legros, Javad Amirian, Fabien Grzeskowiak, Ceilidh Hoffmann, Marie Babel, Jean Bernard Hayet, Julien Pettré.

Title: Robot navigation in dense crowds

Programme: H2020

Duration: Jan 2018 - Jun 2021

Coordinator: Inria

Partners: UCL (UK), SoftBank Robotics (France), Univ. Aachen (Germany), EPFL (Switzerland), ETHZ (Switzerland), Locomotec (Germany)

Inria contact: Julien Pettré

Abstract: CROWDBOT will enable mobile robots to navigate autonomously and assist humans in crowded areas. Today’s robots are programmed to stop when a human, or any obstacle is too close, to avoid coming into contact while moving. This prevents robots from entering densely frequented areas and performing effectively in these high dynamic environments. CROWDBOT aims to fill in the gap in knowledge on close interactions between robots and humans during navigation tasks. The project considers three realistic scenarios: 1) a semi-autonomous wheelchair that must adapt its trajectory to unexpected movements of people in its vicinity to ensure neither its user nor the

pedestrians around it are injured; 2) the commercially available Pepper robot that must navigate in a dense crowd while actively approaching people to assist them; 3) the under development robot *cuyBot* will adapt to compact crowd, being touched and pushed by people. These scenarios generate numerous ethical and safety concerns which this project addresses through a dedicated Ethical and Safety Advisory Board that will design guidelines for robots engaging in interaction in crowded environments. CROWDBOT gathers the required expertise to develop new robot capabilities to allow robots to move in a safe and socially acceptable manner. This requires achieving step changes in a) sensing abilities to estimate the crowd motion around the robot, b) cognitive abilities for the robot to predict the short term evolution of the crowd state and c) navigation abilities to perform safe motion at close range from people. Through demonstrators and open software components, CROWDBOT will show that safe navigation tasks can be achieved within crowds and will facilitate incorporating its results into mobile robots, with significant scientific and industrial impact. By extending the robot operation field toward crowded environments, we enable possibilities for new applications, such as robot-assisted crowd traffic management.

9.3.1.5. H2020 FET-OPEN H-Reality

Participants: Claudio Pacchierotti, Paolo Robuffo Giordano, François Chaumette, Anatole Lécuyer [Hybrid], Maud Marchal [Hybrid].

Title: Mixed Haptic Feedback for Mid-Air Interactions in Virtual and Augmented Realities

Programme: H2020

Duration: October 2018 - September 2021

Coordinator: Univ. Birmingham (UK)

Partners: Univ. Birmingham (UK, coordinator), TU Delft (NL), Ultrahaptics (UK) and Actronika SAS (France)

CNRS contact: Claudio Pacchierotti

Abstract: Digital content today remains focused on visual and auditory stimulation. Even in the realm of VR and AR, sight and sound remain paramount. In contrast, methods for delivering haptic (sense of touch) feedback in commercial media are significantly less advanced than graphical and auditory feedback. Yet without a sense of touch, experiences ultimately feel hollow, virtual realities feel false, and Human-Computer Interfaces become unintuitive. Our vision is to be the first to imbue virtual objects with a physical presence, providing a revolutionary, untethered, virtual-haptic reality: H-Reality. The ambition of H-Reality will be achieved by integrating the commercial pioneers of ultrasonic “non-contact” haptics, state-of-the-art vibrotactile actuators, novel mathematical and tribological modelling of the skin and mechanics of touch, and experts in the psychophysical rendering of sensation. The result will be a sensory experience where digital 3D shapes and textures are made manifest in real space via modulated, focused, ultrasound, ready for the untethered hand to feel, where next-generation wearable haptic rings provide directional vibrotactile stimulation, informing users of an object’s dynamics, and where computational renderings of specific materials can be distinguished via their surface properties. The implications of this technology will be far-reaching. The computer touch-screen will be brought into the third dimension so that swipe gestures will be augmented with instinctive rotational gestures, allowing intuitive manipulation of 3D data sets and strolling about the desktop as a virtual landscape of icons, apps and files. H-Reality will transform online interactions; dangerous machinery will be operated virtually from the safety of the home, and surgeons will hone their skills on thin air.

9.3.2. Collaborations in European Programs, Except FP7 & H2020

9.3.2.1. Interreg Adapt

Participants: Nicolas Le Borgne, Marie Babel.

Programme: Interreg VA France (Channel) England

Project acronym: Adapt

Project title: Assistive Devices for empowering disAbled People through robotic Technologies

Duration: Jan 2017 - Jun 2021

Coordinator: ESIGELEC/IRSEEM Rouen

Other partners: INSA Rennes - IRISA, LGCGM, IETR (France), Université de Picardie Jules Verne - MIS (France), Pôle Saint Héliier (France), CHU Rouen (France), Réseau Breizh PC (France), Pôle TES (France), University College of London - Aspire CREATE (UK), University of Kent (UK), East Kent Hospitals Univ NHS Found. Trust (UK), Health and Europe Centre (UK), Plymouth Hospitals NHS Trust (UK), Canterbury Christ Church University (UK), Kent Surrey Sussex Academic Health Science Network (UK), Cornwall Mobility Center (UK).

Abstract: This project aims to develop innovative assistive technologies in order to support the autonomy and to enhance the mobility of power wheelchair users with severe physical/cognitive disabilities. In particular, the objective is to design and evaluate a power wheelchair simulator as well as to design a multi-layer driving assistance system.

9.3.3. Collaborations with Major European Organizations

9.3.3.1. ANR Opmops

Participants: Florian Berton, Julien Bruneau, Julien Pettré.

Programme: ANR

Project acronym: Opmops

Project title: Organized Pedestrian Movement in Public Spaces: Preparation and Crisis Management of Urban Parades and Demonstration Marches with High Conflict Potential

Duration: June 2017 - June 2020

Coordinator: Université de Haute Alsace (for France), Technische Universität Kaiserslautern (for Germany)

Other partners: Gendarmerie Nationale, Hochschule München, ONHYS S.A.S, Polizei Rheinland-Pfalz, Universität Koblenz-Landau, VdS GmbH

Abstract: This project is about parades of highly controversial groups or of political demonstration marches that are considered as a major threat to urban security. Due to the movement of the urban parades and demonstration marches (in the following abbreviated by UPM) through large parts of cities and the resulting space and time dynamics, it is particularly difficult for forces of civil security (abbreviated in the following by FCS) to guarantee safety at these types of urban events without endangering one of the most important indicators of a free society. In this proposal, partners representing the FCS (police and industry) will cooperate with researchers from academic institutions to develop a decision support tool which can help them both in the preparation phase and crisis management situations of UPMs. Specific technical issues which the French-German consortium will have to tackle include the following: Optimization methods to plan UPM routes, transportation to and from the UPM, location and personnel planning of FCS, control of UPMs using stationary and moving cameras, and simulation methods, including their visualization, with specific emphasis on social behavior.

9.3.3.2. iProcess

Participants: Agniva Sengupta, François Chaumette, Alexandre Krupa, Eric Marchand, Fabien Spindler.

Project acronym: i-Process

Project title: Innovative and Flexible Food Processing Technology in Norway

Duration: January 2016 - December 2019

Coordinator: Sintef (Norway)

Other partners: Nofima, Univ. of Stavanger, NMBU, NTNU (Norway), DTU (Denmark), KU Leuven (Belgium), and about 10 Norwegian companies.

Abstract: This project is granted by the Norwegian Government. Its main objective is to develop novel concepts and methods for flexible and sustainable food processing in Norway. In the scope of this project, the Rainbow group is involved for visual tracking and visual servoing of generic and potentially deformable objects (see Section 7.1.2). Agniva Sengupta spent a 2-month visit at Sintef from March to April 2018.

9.3.3.3. *activeVISION*

Participants: Alexandre Krupa, François Chaumette, Eric Marchand, Agniva Sengupta, Fabien Spindler.

Project acronym: activeVISION

Project title: Active perception and 3D pose estimation of compliant deformable objects applicable to agricultural and ocean space sector

Duration: January 2018 - December 2018

Coordinator: Inria Rennes - Bretagne Atlantique and Sintef (Norway)

Abstract: This project is granted by the PHC Aurora 2018 program that provides travel funds for exchange between France and Norway. It concerns the development of active perception methodology by means of visual servoing for localization and exploration of the scene and the object(s) of interest. Alexandre Krupa and Fabien Spindler spent a 1-week visit at Sintef in Trondheim in March 2018. Prof. Ekrem Misimi from Sintef spent a 3-month visit in Rainbow from May to July 2018.

9.4. International Initiatives

9.4.1. *Inria Associate Teams Not Involved in an Inria International Labs*

9.4.1.1. *ISI4NAVE*

Title: Innovative Sensors and adapted Interfaces for assistive NAVigation and pathology Evaluation
International Partner (Institution - Laboratory - Researcher):

UCL London (United Kingdom) - Aspire CREATE laboratory - Tom Carlson

Duration: Jan 2016 – Dec 2018

See also: <https://team.inria.fr/isi4nave/>

Abstract: The global ageing population, along with disability compensation constitute major challenging societal and economic issues. In particular, achieving autonomy remains a fundamental need that contributes to the individual's wellness and well-being. In this context, innovative and smart technologies are designed to achieve independence while matching user's individual needs and desires.

Hence, designing a robotic assistive solution related to wheelchair navigation remains of major importance as soon as it compensates partial incapacities. This project will then address the following two issues. First, the idea is to design an indoor / outdoor efficient obstacle avoidance system that respects the user intention, and does not alter user perception. This involves embedding innovative sensors to tackle the outdoor wheelchair navigation problem. The second objective is to take advantage of the proposed assistive tool to enhance the user Quality of Experience by means of biofeedback. Indeed, adapted interfaces should improve the understanding of people that suffer from cognitive and/or visual impairments.

The originality of the project is to continuously integrate medical validation as well as clinical trials during the scientific research work in order to match user needs and acceptance.

9.4.2. *Participation in Other International Programs*

9.4.2.1. *ACRV*

François Chaumette is one of the five external experts of the Australian Center for Robotic Vision (see <http://roboticvision.org>). This center groups QUT in Brisbane, ANU in Canberra, Monash University and Adelaide University. In the scope of this project, Agniva Sengupta and Axel Lopez Gandia received a grant to participate to the 2018 Robotic Vision Summer School in Kioloa (New South Wales) and spent a 1-week visit at QUT in March 2018.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

9.5.1.1. Visiting Researchers

- Claudia Elvira Esteves Jaramillo (University of Guanajuato, Mexico) from Jan 2018 until Dec 2018

9.5.1.2. Internships

- Giuseppe Sirignano (Univ. Salerno, Italy), until March 2018
- Mario Selvaggio (Univ. Naples, Italy), from October 2018 until December 2018
- Catalin Stefan Teodorescu (UCL London, UK) from November 2018 until December 2018 in the scope of the Inria Associate team ISI4NAVE (see Section 9.4.1.1)
- Noe Aldana Murillo (CIMAT, Mexico), from Sep 2018
- Jiuyang Bai (Inria), Jun 2018
- Marco Ferro (University of Rome “La Sapienza”, Italy) from Feb 2018 until Aug 2018
- Kaixiang Zhang (University of Zhejiang, China) until Jul 2018

9.5.2. Visits to International Teams

9.5.2.1. Research Stays Abroad

- Firas Abi-Farraj spent a 6-month visit at the Institute of Robotics and Mechatronics of DLR (Münich, Germany) where he worked on the humanoid robot TORO in the scope of his Ph.D. (see [50]).
- Agniva Sengupta spent a 2-month visit at Sintef in Trondheim where he worked on the tracking of deformable objects using a RGB-D camera in the scope of his Ph.D. (see Section 7.1.2).

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- Marie Babel was the General Chair of the 2018 IROS Workshop on “Assistance and Service Robotics in a Human Environment”, Madrid, Spain, co-organized by Fabio Morbidi (MIS, Université Picardie Jules Verne), Francis Colas (Inria Nancy), David Daney (Inria Bordeaux) and Samer Mohammed (LISSI, Université of Paris-Est Creteil).
- Marie Babel was the Scientific Chair and the General co-Chair of the workshop “Robots d’assistance, handicap et vie quotidienne” organized in Inria Rennes on December 7th 2018.

10.1.1.2. Member of the Organizing Committees

- Paolo Robuffo Girodano co-organized with P. Salaris (Inria Sophia-Antipolis) and R. Spica (Stanford University) the workshop “The interplay between optimal estimation for improved action and optimal action for improved estimation” at the 2018 International Conference on Robotics and Automation, Brisbane, Australia
- Paolo Robuffo Girodano is Area Chair for RSS 2019 and Program Chair for MRS 2019
- Claudio Pacchierotti was the Publicity Chair of the Asiahaptics conference held in Songdo, Republic of Korea. He was also Award Co-Chair (Best Poster), and Session Co-Chair at Eurohaptics, Pisa, Italy. He also co-organized the Cross-Cutting Challenge “Expanding sensory interactions: the path to intelligent clothes and objects able to change the way we communicate with the world” at the IEEE Haptics Symposium, San Francisco, USA. Finally, he co-organized the workshop on ‘Haptic-enabled shared control of robotic systems: a compromise between teleoperation and autonomy’ at IROS in Madrid, Spain and the workshop on “Wearable and portable haptics for VR and AR” at IEEE VR in Reutlingen, Germany.

- François Chaumette organized the tutorial on Vision-based Robot Control at the 2018 International Conference on Robotics and Automation, Brisbane, Australia. (<https://team.inria.fr/rainbow/en/icra18-tutorial-vbrc>)

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Claudio Pacchierotti: Eurohaptics (Associate Editor)
- Paolo Robuffo Giordano: ICRA 2019 (Associate Editor)
- Eric Marchand: Orasis 2018
- François Chaumette: ICRA 2019 (Associate Editor)
- Alexandre Krupa: BioRob 2018 (Editor)
- Julien Pettré: IEEE VR 2019

10.1.2.2. Reviewer

- Claudio Pacchierotti: HAPTICS 2018, Eurohaptics 2018, ICRA 2018, IROS 2018, also Senior Reviewer for IEEE Robotics & Automation Society Young Reviewers Program (from 2016)
- Alexandre Krupa: IROS 2018 (1), ICRA 2019 (1)
- Paolo Robuffo Giordano: RSS 2018 (4), ICRA 2019 (2), ECC 2019 (1)
- Marie Babel: ICRA 2018 (1), SMC 2018 (2), IROS 2018 (2), ICRA 2019 (3)
- Vincent Drevelle: IROS 2018 (2), ICRA 2019 (1), AIM 2018 (1)
- Eric Marchand: IROS 2018 (1), ICRA 2018 (2), ICRA 2019 (2)
- François Chaumette: IROS 2018 (1), CDC 2018 (1)
- Julien Pettré: ACM SIGGRAPH 2018 (1), ACM SIGGRAPH Asia 2018 (1), Eurographics 2019 (1), IEEE VR 2019 (6)

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Paolo Robuffo Giordano is Associate Editor for the IEEE Transactions on Robotics
- Paolo Robuffo Giordano is Guest Editor for the Special Issue on “Multi-Robot and Multi-Agent Systems” in Autonomous Robots, 2018
- Claudio Pacchierotti has been Guest Associate Editor of the IEEE Transactions on Haptics for the Special Issue on Wearable and Hand-held Haptics.
- Alexandre Krupa is Associate Editors of the IEEE Robotics and Automation Letters.
- Eric Marchand was an Associate Editor of IEEE Robotics and Automation Letters (RA-L) (till august 2018)
- Eric Marchand is a Senior Editor of IEEE Robotics and Automation Letters (RA-L) (from august 2018)
- Eric Marchand is an Editor for Interstices)i(
- François Chaumette: Senior Editor of the IEEE Trans. on Robotics, Editorial Board of the Int. Journal of Robotics Research, Founding Senior Editor of the IEEE Robotics and Automation Letters till June 2018, Editorial Board of the Springer Tracts in Advanced Robotics, and Board Member of the Springer Encyclopedia of Robotics.

10.1.3.2. Reviewer - Reviewing Activities

- Claudio Pacchierotti: JMRR (2), TOH (7), THMS (1), TIM (1), RAL (5), TBME (3), TMECH (1), IJMRCAS (1), IJCARS (1), Plos One (1), Journal of Engineering in Medicine (3), Wiley Interdisciplinary Reviews: Cognitive Science (2), Mechatronics (1), IJHCI (4), Advanced Robotics (1), International Journal of Advanced Robotic Systems (2), Endoscopy International Open (2), Frontiers in Robotics and AI (1)

- Paolo Robuffo Giordano: IEEE TRO (1), IEEE T-CYB (1), IEEE TCST (2), IEEE RAL (3), IJRR (1), IJC (1), AURO (1)
- Eric Marchand: CVIU (1)
- François Chaumette: IEEE TIE (4), IEEE RA-L (2)
- Julien Pettré: Graphical Models (1), Frontiers in Robotics and AI (1), IEEE TVCG (1)

10.1.4. Invited Talks

- Paolo Robuffo Giordano:
 - “Human-assisted robotics”. H. H. Bühlhoff’s Farewell Symposium - Flies, Men and Machines: A Scientific Adventure, Tübingen, Germany, August 2018
 - “Blending Human Assistance and Local Autonomy for Advanced Telemanipulation”. IROS 2018 Workshop on Haptic-enabled shared control of robotic systems: a compromise between teleoperation and autonomy, October 2018 [47]
 - “Formation Control and Localization with Onboard Sensing and Local Communication”. IROS 2018 Workshop on Multi-Robot Perception- Driven Control and Planning, October 2018 [48]
 - “Physical Interpretation of Rigidity for Bearing Formations”, Second Workshop “Rigidity Theory for Multi-Agent Systems meets Parallel Robotics”, Nantes, France
- Claudio Pacchierotti:
 - “Our wearable haptics experience: story, insights, and open questions” Workshop “User-Centered Methods in Human-Robot Interaction” at IROS Conference, Madrid, Spain, 2018.
 - “Haptic feedback and robotic procedures” 10th Annual meeting on Robotic Gynaecological Surgery of the Society of European Robotic Gyneacological Surgery (SERGS), Milan, Italy, 2018.
 - “Cutaneous haptic feedback in robotic medical procedures.” Presentation to Titan Medical Inc., Strasbourg, France, 2018.
 - “Wearable haptics for virtual and augmented reality: applications in the entertainment and robotic fields” Robotics Research Jam Sessions at the University of Pisa, Pisa, Italy, 2018.
 - “Wearable fingertip haptics for mixed reality.” University of Aarhus, Herning, Denmark, 2018.
 - “Haptic feedback in robotic procedures: current work and perspectives.” Congress of the Society of Endometriosis and Uterine Disorders, Florence, Italy, 2018.
 - “The future of haptic feedback in robotic procedures.” Beyond Gynecologic Surgery conference, Clermont-Ferrant, France, 2018.
 - “Wearable fingertip haptics for Virtual Reality.” Workshop on “Wearable and portable haptics for VR and AR”, IEEE International Conference on Virtual Reality (VR), Reutlingen, Germany, 2018.
- François Chaumette:
 - “Visual servoing with and without image processing”, 1st Symposium on Intelligent Robots: Autonomy and Vision, Abu-Dhabi, March 2018 [46]
 - “Geometric and photometric vision-based robot control: modeling approach”, ICRA 2018 Tutorial on Vision-based Robot Control, Brisbane, May 2018 [45]
 - “Geometric and end-to-end visual servoing”, Plenary talk at IEEE Int. Conf. on CYBER Technology in Automation, Control, and Intelligent Systems, Tianjin, China, July 2018 [44]
- Fabien Spindler

- “Vision-based robot control with ViSP”, ICRA 2018 Tutorial on Vision-based Robot Control, Brisbane, May 2018 [49]

10.1.5. Leadership within the Scientific Community

- Claudio Pacchierotti is the Chair of the IEEE Technical Committee on Haptics, and Secretary of the Eurohaptics Society.
- François Chaumette is a 2016-2018 elected member of the Administrative Committee of the IEEE Robotics and Automation Society. He is also a nominated member of the Scientific Council of the CNRS INS2I, a member of the Scientific Council of RTE Vedecom, and a founding member of the Scientific Council of the “GdR Robotique”.

10.1.6. Scientific Expertise

- Alexandre Krupa was reviewer of an ANR project (Generic project call 2018)
- Paolo Robuffo Giordano was reviewer for evaluating proposals of the ANR (French National Research Agency), NWO (Netherlands Organisation for Scientific Research), SNSF (Swiss National Science Foundation), MIUR (Italian National Research Agency)
- Marie Babel served as an expert for the International Mission of the French Research Ministry (MEIRIES) - Campus France
- Vincent Drevelle has been reviewer of an ANR ASTRID project
- François Chaumette served as member of IEEE RAS Pioneer Award Evaluation Panel and IEEE RAS Awards Evaluation Panel. He was a panel member of the 2018 ICREA Academia program (similar to IUF for Catalonia). He was also involved in the evaluation of a research proposal submitted to the Research Foundation of Flanders.

10.1.7. Research Administration

- Alexandre Krupa is a member of the CUMIR (“Commission des Utilisateurs des Moyens Informatiques pour la Recherche”) of Inria Rennes-Bretagne Atlantique. Alexandre Krupa also serves as Inria representative (correspondent) at the IRT Jules Verne.
- Eric Marchand served as secretary in the board of the “Association Française pour la Reconnaissance et l’interprétation des Formes” (AFRIF). He was also in charge of the Irisa Ph.D. students in the committee in charge of all the temporary recruitments (“Commission Personnel”) at Inria Rennes-Bretagne Atlantique and Irisa (till september 2018). He is in the board of the “Ecole doctorale Matisse”. He is the head of "Digital Signals and Images, Robotics" department at IRISA (from june 2018).
- François Chaumette serves as 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, and of the Scientific Steering Committee (COSS) of IRISA.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Marie Babel:

Master INSA2: “Robotics”, 26 hours, M1, INSA Rennes

Master INSA1: “Architecture”, 30 hours, L3, INSA Rennes

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

Master INSA1: “Practical studies”, 16 hours, M1, INSA Rennes

Master INSA2: “Image analysis”, 18 hours, M1, INSA Rennes

Master INSA1: “Remedial math courses”, 50 hours, L3, INSA Rennes

François Chaumette:

Master SISEA: “”, 12 hours, M2, Université de Rennes 1

Master ENS: “Visual servoing”, 6 hours, M1, Ecole Nationale Supérieure de Rennes

Master ESIR3: “Visual servoing”, 8 hours, M2, Ecole supérieure d’ingénieurs de Rennes

Vincent Drevelle:

Master ESIR2: “Real-time systems and RTOS”, 24 hours, M1, Esir Rennes

Master ILA: “Terrain information systems”, 30 hours, M2, Université de Rennes 1

Master Info: “Artificial intelligence”, 20 hours, M1, Université de Rennes 1

Licence Info: “Computer systems architecture”, 22 hours, L1, Université de Rennes 1

Master Elec: “Electronics project”, 8 hours, M1, Université de Rennes 1

Portail Info-Elec: “Discovering programming and electronics”, 14 hours, L1, Université de Rennes 1

Licence Miage: “Computer programming”, 78 hours, L3, Université de Rennes 1

Master Elec: “Instrumentation, localization, GPS”, 4 hours, M2, Université de Rennes 1

Master Elec: “Multisensor data fusion”, 20 hours, M2, Université de Rennes 1

Master IL: “Mobile robotics”, 32 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

Master INSA1: “Programmation Informatique”, 42 hours, INSA Rennes

Master ESIR3: “Ultrasound visual servoing”, 9 hours, M2, Esir Rennes

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 ENS: “Computer vision”, 16 hours, M2, ENS Rennes

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

Julien Pettré:

Master SIF: "Motion for Animation and Robotics", 6 hours, Université de Rennes 1

Master Artificial Intelligence and Advanced Visual Computing: "Advanced 3D graphics", 3 hours, Ecole Polytechnique

10.2.2. Supervision

- Ph.D. in progress: Quentin Delamare, “Algorithmes d’estimation et de commande pour des quadrirotors en interaction physique avec l’environnement”, started in September 2016, supervised by Paolo Robuffo Giordano and Antonio Franchi (LAAS)
- Ph.D. in progress: Rahaf Rahal, “Mixed tactile-force feedback for safe and intuitive robotic teleoperation”, started in October 2017, supervised by Paolo Robuffo Giordano and Claudio Pacchierotti
- Ph.D. in progress: Alexander Oliva, “Coupling Vision and Force for Robotic Manipulation”, started in October 2018, supervised by François Chaumette and Paolo Robuffo Giordano
- Ph.D. in progress: Axel Lopez Gandia, “Data assimilation for synthetic vision-based crowd simulation algorithms”, started in October 2016, supervised by Julien Pettré and François Chaumette
- Ph.D. in progress: Zane Zake (IRT Jules Verne), “Visual servoing for cable-driven parallel robots”, started in January 2018, supervised by Stéphane Caro (LS2N) and François Chaumette
- Ph.D. in progress: Xavier De Tinguy de la Giroulière, “Conception de techniques d’interaction multisensorielles pour la manipulation dextre d’objets en réalité virtuelle”, started in September 2017, supervised by Maud Marchal, Anatole Lécuyer (Hybrid group) and Claudio Pacchierotti
- Ph.D. in progress: Gerard Gallagher, “Haptic-enabled interaction techniques for Mixed Reality applications”, started in October 2018, supervised by Maud Marchal, Anatole Lécuyer (Hybrid group) and Claudio Pacchierotti
- Ph.D. in progress: Hadrien Gurnel “Haptic guidance of a biopsy needle”, started in October 2016, supervised by Alexandre Krupa, Maud Marchal (Hybrid team) and Laurent Launay (IRT b<>com)
- Ph.D. in progress: Agniva Sengupta, “Localization and characterization of objects with unknown shapes”, started in January 2017, supervised by Alexandre Krupa and Eric Marchand
- Ph.D. in progress: Romain Lagneau (Hybrid team), “Data-driven models for detexterous manipulation of robots”, started in October 2017, supervised by Alexandre Krupa and Maud Marchal (Hybrid team)
- Ph.D. in progress: Guillaume Vailland, “Outdoor wheelchair assisted navigation: reality versus virtuality”, started in November 2018, supervised by Marie Babel and Valérie Gouranton (Hybrid team)
- Ph.D. in progress: Salma Jiddi, “Photometric Registration of Indoor Real Scenes using an RGB-D Camera with Application to Mixed Reality”, to be defended in January 2019, supervised by Eric Marchand
- Ph.D. in progress: Ide-Flore Kenmogne “Localisation ensembliste de drones à l’aide de méthodes par intervalles”, to be defended in January 2019, supervised by Eric Marchand and Vincent Drevelle
- Ph.D. in progress: Xi Wang “Robustness of Visual SLAM techniques to light changing conditions”, started in September 2018, supervised by Eric Marchand and Marc Christie
- Ph.D. in progress: Agniva Sengupta “”, to be defended in January 2020, supervised by Eric Marchand and Alexandre Krupa
- Ph.D. in progress: Nicolas Le Borgne, “Contrôle partagé et navigation assistée d’un fauteuil roulant en extérieur”, started in October 2017, supervised by Marie Babel
- Ph.D. in progress: Aline Baudry, “Contribution à la modélisation des fauteuils roulants pour l’amélioration de leur navigation en mode semi-autonome”, started in October 2016, supervised by Marie Babel and Sylvain Guégan (Mechanical Engineering Dpt/LGCGM at Insa Rennes)
- Ph.D. in progress: Axel Lopez, “Character navigation based on optical flow”, started in October 2016, supervised by François Chaumette and Julien Pettré
- Ph.D. in progress: Javad Amirian, “Crowd motion prediction for robot navigation in dense crowds”, started in January 2018, supervised by Jean-Bernard Hayet and Julien Pettré

- Ph.D. in progress: Fabien Grzeskowiak, “Crowd simulation for testing robot navigation in dense crowds”, started in October 2018, supervised by Marie Babel and Julien Pettré
- Ph.D. in progress: Florian Berton, “Gaze analysis for crowd behaviours study”, started in October 2017, supervised by Anne-Hélène Olivier, Ludovic Hoyet and Julien Pettré
- Ph.D. defended: Pedro Patlan-Rosales, “A robotic control framework for quantitative ultrasound elastography”, defended in January 2018, supervised by Alexandre Krupa [5]
- Ph.D. defended: Lesley-Ann Dufлот, “Direct visual servoing using shearlet and wavelet transforms of the image”, defended in July 2018, supervised by Alexandre Krupa and Brahim Tamadazte (Minarob group at FEMTO-ST, Besançon) [4]
- Ph.D. defended: Fabrizio Schiano, “Bearing-based Localization and Control for Multiple Quadrotor UAVs”, defended in January 2018, supervised by P. Robuffo Giordano [7]
- Ph.D. defended: Louise Devigne, “Low-cost robotic solutions for safe assisted power wheelchair navigation: towards a contribution to neurological rehabilitation”, defended in December 2018, supervised by Marie Babel and Philippe Gallien (Pôle Saint Hélier)
- Ph.D. defended: Quentin Bateux, “Going further with direct visual servoing”, defended in January 2018, supervised by Eric Marchand [2]
- Ph.D. defended: Guillaume Cortes, “Contribution to the study of projection-based systems for industrial applications in mixed reality”, defended in October 2018, supervised by Eric Marchand and Anatole Lécuyer [Hybrid]
- Ph.D. defended: Firas Abi Farraj, “Contributions to Shared Control Architectures for Advanced Telemanipulation”, defended in December 2018, supervised by Paolo Robuffo Giordano [1]
- Ph.D. defended: Bryan Penin “Contributions to optimal and reactive vision-based trajectory generation for a quadrotor UAV”, defended in December 2018, supervised by Paolo Robuffo Giordano and François Chaumette [6]

10.2.3. Juries

- Claudio Pacchierotti: Lucia Schiatti (Ph.D., member, IIT, Genova, Italy), Matteo Rossi (Ph.D., member, Univ. Pisa, Pisa, Italy)
- Alexandre Krupa: Yinoussa Adagolodjo (Ph.D., reviewer, Univ. de Strasbourg, ICube)
- Paolo Robuffo Giordano: Nicolas Staub (Ph.D., member, LAAS-CNRS), Fabrizio Boriero (Ph.D., reviewer, Univ. Verona, Italy)
- Marie Babel: Francesco Barbosa Anda (Ph.D., member, LAAS, Toulouse), Dinh Nguyen Van (Ph.D., member, UPMC, Paris).
- Eric Marchand: Alexandre Morgand, (PhD, reviewer, univ. Clermont Auvergne) ; Sudhanya Chatterjee, (Ph.D. president, univ. de Rennes 1) ; Musaab Khalid, (Ph.D. president, Irstea Lyon) ; Romain Brégier, (Ph.D. president, INPG) ; Bogdan Khomutenko, (Ph.D. president, École centrale de Nantes) ; Lesley-Ann Dufлот, (Ph.D. president, univ. de Rennes 1) ; Pedro Patlan-Rosales, (Ph.D. president, univ. de Rennes 1) ;
- François Chaumette: Davide Nicolis (Ph.D., Politecnico di Milano, reviewer), Marco Ferro (Ph.D., Univ La Sapienza, Roma, reviewer), Firas Abi-Farraj (Ph.D., president, Univ de Rennes 1)
- Julien Pettré: Pierre Fernbach (Ph.D. member, Univ. Toulouse Paul Sabatier, Laas)

10.3. Popularization

- Due to the visibility of our experimental platforms, the team is often requested 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, grasping and dual arm manipulation by Romeo, vision-based shared control using our haptic device for object manipulation, the control of a fleet of quadrotors, vision-based detection and tracking for space navigation in a rendezvous context, the semi-autonomous navigation of a wheelchair, and augmented reality applications. Some of these demonstrations are available as videos on VispTeam YouTube channel (<https://www.youtube.com/user/VispTeam/videos>).

- In October Firas Abi Farraj, Marco Aggravi, Claudio Pacchierotti and Fabien Spindler attended to the “Maker Fair” even in Rome (<https://2018.makerfairerome.eu/it/>) presenting various vision-based and shared control robotic demonstrations with Viper and Franka arms and haptic devices.
- Eric Marchand is an editor for Interstices)i(

10.3.1. Interventions

- Marie Babel participated to the Science Festival in October 2018 and animated an interactive animation session for general public organized in Acigné, France
- Solenne Fortun participated to the Tech’in Vitré forum with an interview in March 2018.
- Marie Babel animated an interactive session organized in INSA Rennes about "Women in Sciences" on December 19th, 2018 for female students.

11. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

- [1] F. ABI-FARRAJ. *Contributions to Shared Control Architectures for Advanced Telemanipulation*, Université de Rennes 1 [UR1], December 2018, <https://tel.archives-ouvertes.fr/tel-01972381>
- [2] Q. BATEUX. *Going further with direct visual servoing*, Université Rennes 1, February 2018, <https://tel.archives-ouvertes.fr/tel-01764148>
- [3] G. CORTES. *Contribution to the Study of Projection-based Systems for Industrial Applications in Mixed Reality*, Université de Rennes 1, October 2018, <https://tel.archives-ouvertes.fr/tel-01969726>
- [4] L.-A. DUFLOT. *Direct visual servoing using shearlet and wavelet transforms of the image*, Université Rennes 1, July 2018, <https://tel.archives-ouvertes.fr/tel-01861464>
- [5] P. A. PATLAN-ROSALES. *A robotic control framework for quantitative ultrasound elastography*, Université Rennes 1, January 2018, <https://tel.archives-ouvertes.fr/tel-01718721>
- [6] B. PENIN. *Contributions to optimal and reactive vision-based trajectory generation for a quadrotor UAV*, Université de Rennes 1 [UR1], December 2018, <https://tel.archives-ouvertes.fr/tel-01972349>
- [7] F. SCHIANO. *Bearing-based localization and control for multiple quadrotor UAVs*, Université Rennes 1, January 2018, <https://tel.archives-ouvertes.fr/tel-01780065>

Articles in International Peer-Reviewed Journals

- [8] M. AGGRAVI, F. PAUSÉ, P. ROBUFFO GIORDANO, C. PACCHIEROTTI. *Design and Evaluation of a Wearable Haptic Device for Skin Stretch, Pressure, and Vibrotactile Stimuli*, in "IEEE Robotics and Automation Letters", July 2018, vol. 3, n^o 3, pp. 2166-2173 [DOI : 10.1109/LRA.2018.2810887], <https://hal.inria.fr/hal-01717248>
- [9] G. ANTONELLI, E. CATALDI, F. ARRICHELLO, P. ROBUFFO GIORDANO, S. CHIAVERINI, A. FRANCHI. *Adaptive Trajectory Tracking for Quadrotor MAVs in Presence of Parameter Uncertainties and External Disturbances*, in "IEEE Transactions on Control Systems Technology", January 2018, vol. 26, n^o 1, pp. 248-254 [DOI : 10.1109/TCST.2017.2650679], <https://hal.inria.fr/hal-01483653>

- [10] M. BAKTHAVATCHALAM, O. TAHRI, F. CHAUMETTE. *A Direct Dense Visual Servoing Approach using Photometric Moments*, in "IEEE Transactions on Robotics", October 2018, vol. 34, n^o 5, pp. 1226-1239 [DOI : 10.1109/TRO.2018.2830379], <https://hal.inria.fr/hal-01758205>
- [11] M. CHAUHAN, N. DESHPANDE, C. PACCHIEROTTI, L. MELI, D. PRATTICHIZZO, D. CALDWELL, L. S. MATTOS. *A robotic microsurgical forceps for transoral laser microsurgery*, in "International Journal of Computer Assisted Radiology and Surgery", 2018, pp. 1-13, <https://hal.inria.fr/hal-01940752>
- [12] J. CHEVRIE, N. SHAHRIARI, M. BABEL, A. KRUPA, S. MISRA. *Flexible Needle Steering in Moving Biological Tissue with Motion Compensation using Ultrasound and Force Feedback*, in "IEEE Robotics and Automation Letters", May 2018, vol. 3, n^o 3, pp. 2338 - 2345 [DOI : 10.1109/LRA.2018.2809484], <https://hal.inria.fr/hal-01717915>
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Invited Conferences

- [44] F. CHAUMETTE. *Geometric and end-to-end visual servoing*, in "Plenary Talk: CYBER 2018 - IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems", Tianjin, China, July 2018, <https://hal.inria.fr/hal-01935409>
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