IN PARTNERSHIP WITH:
CNRS

Institut national des sciences appliquées de Rennes

Université Rennes 1

Activity Report 2019

Project-Team RAINBOW

Sensor-based Robotics and Human Interaction

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

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Robotics and Smart environments

Table of contents

Project-Team RAINBOW

Creation of the Team: 2018 January 01, updated into Project-Team: 2018 June 01

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
A5.5.4. - Animation
A5.6. - Virtual reality, augmented reality
A5.6.1. - Virtual reality
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
A5.10.7. - Learning
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
A9.5. - Robotics
A9.7. - AI algorithmics
A9.9. - Distributed AI, Multi-agent

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

1. Team, Visitors, External Collaborators

Research Scientists

Paolo Robuffo Giordano [Team leader, CNRS, Senior Researcher, HDR]
François Chaumette [Inria, Senior Researcher, HDR]
Alexandre Krupa [Inria, Researcher, HDR]
Claudio Pacchierotti [CNRS, Researcher]
Julien Pettré [Inria, Senior Researcher, HDR]

Faculty Members

Marie Babel [INSA Rennes, Associate Professor, HDR]
Vincent Drevelle [Univ de Rennes I, Associate Professor]
Eric Marchand [Univ de Rennes I, Professor, HDR]
Quentin Delamare [ENS Rennes, Professor, AGPR, from Sep 2019]

Post-Doctoral Fellow

Thomas Howard [CNRS]

PhD Students

Javad Amirian [Inria]
Benoît Antoniotti [Inria]
Florian Berton [Inria]
Pascal Brault [Inria, from Sep 2019]
Adèle Colas [Inria, from Nov 2019]
Quentin Delamare [Univ de Rennes I, until Aug 2019]
Mathieu Gonzalez [IRT B<>Com, from Oct 2019]
Fabien Grzeskowiak [Inria]
Hadrien Gurnel [IRT B<>com, until Oct 2019]
Alberto Jovane [Inria, from Sep 2019]
Axel Lopez Gandia [Univ de Rennes I]
Alexander Oliva [Inria]
Rahaf Rahal [Univ de Rennes I]
Agniva Sengupta [Inria]
Guillaume Vailland [INSA Rennes]

Technical staff

Fabien Spindler [Inria, Engineer]
Firas Abi Farraj [CNRS, until Jun 2019]
Marco Aggravi [CNRS]
Dieudonne Atrevi [Inria, from Nov 2019]
Arianna Bottinelli [Inria, from Feb 2019 until May 2019]
Julien Bruneau [Inria]
Nicolas Cazy [Inria, until Feb 2019]
Marco Cognetti [CNRS, until Nov 2019]
Cedric de Almeida Braga [Inria, from Oct 2019]
Louise Devigne [INSA Rennes]
Solenne Fortun [INSA Rennes]
Ceilidh Hoffmann [Inria, until Mar 2019]
Joudy Nader [CNRS, from Oct 2019]
Noura Neji [Inria, from Sep 2019]
François Pasteau [INSA Rennes]
Ramana Sundararaman [Inria, from Oct 2019]
Wouter Van Toll [Inria, from Jan 2019]

Interns and Apprentices

Alexandre Bonneau [Inria, from Feb 2019 until Jun 2019]
Pascal Brault [Ecole normale supérieure de Rennes, from Feb 2019 until Jun 2019]
Ahmed Elsherif [CNRS, from Feb 2019 until Jul 2019]

Samuel Felton [Inria, from Feb 2019 until Sep 2019]
Gatien Gaumerais [Inria, from Jun 2019 until Sep 2019]
Daniel Lemos Estima [CNRS, from Sep 2019 until Dec 2019]
Giulia Matarese [Univ de Rennes I, from Oct 2018 until Mar 2019]
Valerio Paduano [Univ de Rennes I, from Feb 2019 until Jul 2019]
David Steeven Villa Salazar [CNRS, from Jan 2019 until Jun 2019]
Riccardo Arciulo [University of Rome, from Nov 2019]
Quentin Zanini [CNRS, from Jun 2019 until Aug 2019]

Administrative Assistant

Hélène de La Ruée [Inria]

Visiting Scientist

Ekrem Misimi [Sintef, Norway, Mar 2019 and July 2019]

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 word, 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, 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.

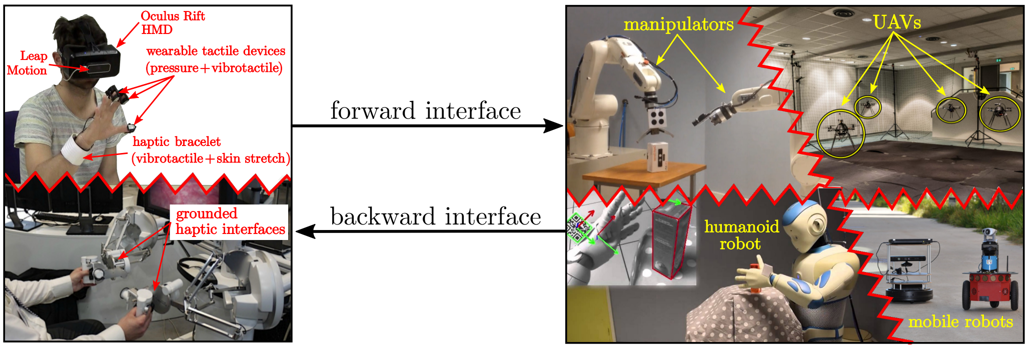


Figure 1. An illustration of the prototypical activities foreseen in Rainbow in which a human operator is in partial (and high-level) control of single/multiple complex robots performing semi-autonomous tasks

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. Highlights of the Year

4.1. Highlights of the Year

- J. Pettré is the unit PI of the new H2020 ICT project “PRESENT” started on Sep 2019

4.1.1. Awards

- P. Robuffo Giordano received the Prix Michel Monpetit – Inria from the Académie des sciences

- B. Penin (former PhD student), P. Robuffo Giordano and F. Chaumette received at ICRA 2019 the IEEE RA-L 2018 Best Paper Award for the paper “Vision-Based Reactive Planning for Aggressive Target Tracking while Avoiding Collisions and Occlusions”
- M. Babel received the Innovation Award from the Société Française de Médecine physique et de Réadaptation (SOFMER) for the power wheelchair simulator in virtual reality described in Sect. 6.4.6

5. New Software and Platforms

5.1. 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

5.2. 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 2D and 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 acquiring 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 and Fabien Spindler
- Partners: Inria - Université de Rennes 1
- Contact: Alexandre Krupa
- URL: https://ustk.inria.fr

5.3. 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 designing vision-based tasks for eye-in-hand and eye-to-hand systems from 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 408 examples and 88 tutorials are proposed to the user. ViSP is released under a dual licensing model. It is open-source with a GNU GPLv2 or GPLv3 license. A professional edition license that replaces GNU GPL is also available.

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

5.4. Platforms

5.4.1. Robot Vision Platform

Participants: François Chaumette, Alexandre Krupa, Eric Marchand, Fabien Spindler [contact].

We exploit two industrial robotic systems built by Afma Robots in the nineties to validate our research 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 monocular RGB cameras. The Gantry robot also allows mounting grippers on its end-effector. Attached to this platform, we can also find a collection of various RGB and RGB-D cameras used to validate vision-based real-time tracking algorithms (see Sections 6.1.1 and 6.1.2). Note that four papers [32], [14], [52], [53] published by Rainbow in 2019 include results validated on this platform.

5.4.2. Mobile Robots

Participants: Marie Babel, Solenne Fortun, François Pasteau, Julien Pettré, Quentin Delamare, 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 6.4.4), 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, ultrasound and time of flight 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 a virtual reality environment (see Fig. 3(c)).

Figure 2. Rainbow robotics platform for vision-based manipulation

Pepper, a human-shaped robot designed by SoftBank Robotics to be a genuine day-to-day companion (see Fig. 3.d) 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 6.2.6).

Note that 2 papers and 1 PhD Thesis exploiting the mobile robots were published this year [42], [54], [1].

(a) (b) (c) (d)

Figure 3. Mobile Robot Platform. a) Pioneer P3-DX robot, b) wheelchairs from Permobil, Sunrise and YouQ, c) Wheelchair haptic simulator, d) Pepper human-shaped robot

5.4.3. Medical Robotic Platform

Participants: Alexandre Krupa, Fabien Spindler [contact].

This platform is composed of two 6 DoF Adept Viper arms (see Figs. 4.a–b). Ultrasound probes connected either to a SonoSite 180 Plus or an Ultrasonix SonixTouch 2D and 3D imaging system can be mounted on a force torque sensor attached to each robot end-effector. The haptic Virtuose 6D or Omega 6 device (see Fig. 7.a) can also be used within this platform.

This year this platform was extended with a new ATI Nano43 force/torque sensor dedicated to needle insertion applications.

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 Sect. 6.4.3 and Sect. 6.4.2).

This platform was used to obtain experimental results presented in 4 new papers [6], [23], [38], [51].

(a) (b)

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.

5.4.4. 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.a) to validate our researches in coupling force and vision for controlling robot manipulators (see Section 6.2.12) and in shared control for remote manipulation (see Section 6.4.1). Other haptic devices (see Section 5.4.6) can also be coupled to this platform.

This year this platform was extended with a new Reflex TakkTile 2 gripper from RightHand Labs (see Fig. 5.b). A new force/torque sensor from Alberobotics that can be mounted on the robot end-effector to get more precision during torque control was also bought.

Two new papers published this year include experimental results obtained with this platform [50], [66].

Figure 5. Rainbow advanced manipulation platform. a) One of the two Panda lightweight arms from Franka Emika, with mounted the Pisa SoftHand, b) the Reflex TakkTile 2 gripper that could be mounted on the Panda robot end-effector.

5.4.5. Unmanned Aerial Vehicles (UAVs)

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

Rainbow is involved in several activities involving perception and control for single and multiple quadrotor UAVs. To this end, we purchased four quadrotors from Mikrokopter Gmbh, Germany (see Fig. 6.a), and one quadrotor from 3DRobotics, USA (see Fig. 6.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 2 papers [20], [25] and 2 PhD Theses [3] contain simulative and experimental results obtained with this platform [1].

(a) (b) (c)

Figure 6. Unmanned Aerial Vehicles Platform. a) Quadrotor XL1 from Mikrokopter, b) Quadrotor Iris from 3DRobotics, c) Formation control with 3 XL1 from Mikrokopter.

5.4.6. 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 Virtuose 6D device from Haption (see Fig. 7.a). This device is used as master device in many of our shared control activities (see Sections 6.4.2 and 6.4.3). It could also be coupled to the Haption haptic glove in loan from the University of Birmingham. An Omega 6 (see Fig. 7.b) from Force Dimension and devices in loan from Ultrahaptics complete this platform that could be coupled to the other robotic platforms.

This platform was used to obtain experimental results presented in 9 papers [6], [50], [43], [44], [38], [45], [11], [51], [5] published this year.

6. New Results

6.1. Optimal and Uncertainty-Aware Sensing

6.1.1. Tracking of Rigid Objects of Complex Shapes with a RDB-D Camera

Participants: Agniva Sengupta, Alexandre Krupa, Eric Marchand.

(a)

(b)

Figure 7. Haptics and Shared Control Platform. a) Virtuose 6D and b) Omega 6 haptic devices

In the context of the iProcess project (see Section 8.3.8), we developed a method for accurately tracking the pose of rigid objects of complex shapes using a RGB-D camera [52]. This method only needs a coarse 3D geometric model of the object of interest represented as a 3D mesh. The tracking of the object is based on a joint minimization of geometric and photometric criteria and more particularly on a combination of point-to-plane distance minimization and photometric error minimization. The concept of successive "keyframes" was also used in this approach for minimizing possible drift of the tracking. The proposed approach was validated on both simulated and real data and the results experimentally demonstrated a better tracking accuracy than existing state-of-the-art 6-DoF object tracking methods, especially when dealing with low-textured objects, multiple coplanar faces, occlusions and partial specularities of the scene.

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

Participants: Agniva Sengupta, Alexandre Krupa, Eric Marchand.

This research activity was also carried out in the context of the iProcess project (see Section 8.3.8) and will continue with the recent starting GentleMAN project (see Section 8.3.9). It focusses on the elaboration of approaches able to accurately track in real-time the deformation of soft objects using a RGB-D camera. The state-of-the-art approaches are currently relying on the use of Finite Element Model (FEM) to simulate the physics (mechanical behavior) of the deformable object. However, they suffer from the drawback of being excessively dependent on the accurate knowledge of the physical properties of the object being tracked (Young Modulus, Poisson's ratio, etc). This year, we proposed a first method that only required a coarse physical model of the object based on FEM whose parameters do not need to be precise [53]. The method consists in applying a set of virtual forces on the surface mesh of our coarse FEM model in such a way that it deforms to fit the current shape of the object. A point-to-plane distance error between the point cloud provided by the depth camera and the model mesh is iteratively minimized with respect to these virtual forces. The point of application of force is determined by an analysis of the error obtained from rigid tracking, which is done in parallel with the non-rigid tracking. The approach has been validated on simulated objects with ground-truth, as well on real objects of unknown physical properties and experimentally demonstrated that accurate tracking of deformable objects can be achieved without the need of a precise physical model.

6.1.3. Trajectory Generation for Optimal State Estimation

Participants: Marco Cognetti, 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. Over the last years we have developed a general framework for solving *online* the active sensing problem by continuously replanning an optimal trajectory that maximizes a suitable norm of the Constructibility Gramian (CG), while also coping with a number of constraints including limited energy and feasibility. The results obtained so far have been generalized and summarized in [27], where the online trajectory replanning for CG maximization has been applied to two relevant case studies (unicycle and quadrotor) and validated via a large statistical campaign. 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 manipulator), and to the mutual localization problem for a multi-robot group.

6.1.4. Robotic manipulators in Physical Interaction with the Environment

Participant: Claudio Pacchierotti.

As robotic systems become more flexible and intelligent, they must be able to move into environments with a high degree of uncertainty or clutter, such as our homes, workplaces, and the outdoors. In these unstructured scenarios, it is possible that the body of the robot collides with its surroundings. As such, it would be desirable to characterise these contacts in terms of their location and interaction forces. We worked to address the problem of detecting and isolating collisions between a robotic manipulator and its environment, using only on-board joint torque and position sensing [37]. We presented an algorithm based on a particle filter that, under some assumptions, is able to identify the contact location anywhere on the robot body. It requires the robot to perform small exploratory movements, progressively integrating the new sensing information through a Bayesian framework. The method assumes negligible friction forces, convex contact surfaces, and linear contact stiffness. Compared to existing approaches, it allows this detection to be carried in almost all the surface of the robot's body. We tested the proposed approach both in simulation and in a real environment. Experiments in simulation showed that our approach outperformed two other methods that made simpler assumptions. Experiments in a real environment using a robot with joint torque sensors showed the applicability of the method to real world scenarios and its ability to cope with situations where the algorithm's assumptions did not hold.

6.1.5. 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. Quantifier elimination techniques have been used to consider uncertainty in the landmarks positions without adding pessimism in the computed solution. This work has been applied to cooperative localization of UAVs, based on image and range measurements [20].

6.2. Advanced Sensor-Based Control

6.2.1. Sensor-based Trajectory Planning for quadrotor UAVs

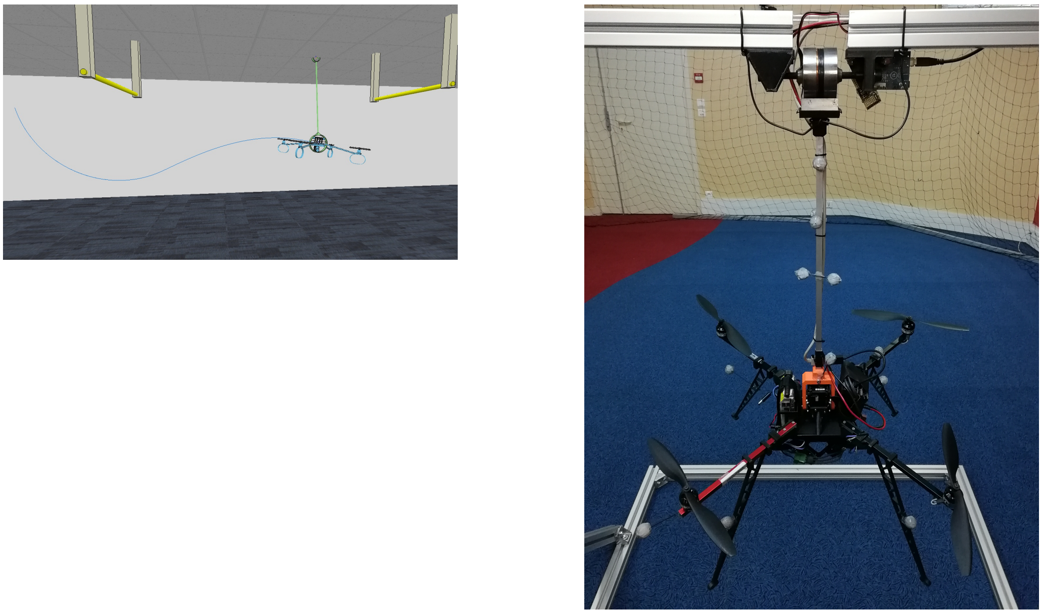
Participants: François Chaumette, Paolo Robuffo Giordano.

In the context of developing robust navigation strategies for quadrotor UAVs with onboard cameras and IMUs, we considered the problem of planning minimum-time trajectors in a cluttered environment for reaching a goal while coping with actuation and sensing constraints [25]. In particular, we considered a realistic model for the onboard camera that considers limited fov and possible occlusions due to obstructed visibility (e.g., presence of obstacles). Whenever the camera can detect landmarks in the environment, the visual cues can be used to drive a state estimation algorithm (a EKF) for updating the current estimation of the UAV state (its pose and velocity). However, beacause of the sensing constraints, the possibility of detecting and tracking the landmarks may be lost while moving in the environment. Therefore, we proposed a robust "perception-aware" planning strategy, based on the bi-directional A* planner,

6.2.2. 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 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. 8(a). We are currently finalizing a real prototype (Fig. 8(b)) for obtaining an experimental validation of the whole approach [1].



(a) (b)

Figure 8. UAVs in Physical Interaction with the Environment. a) The simulated MonkeyRotor performing a hook-to-hook maneuver. b) The prototype currently under finalization.

6.2.3. *Trajectory Generation for Minimum Closed-Loop State Sensitivity*

Participants: Pascal Brault, Quentin Delamare, Paolo Robuffo Giordano.

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. During this year, we have extended the existing minimization framework to also include the notion of “input sensitivity”, which allows to obtain trajectories whose realization (in perturbed conditions) leaves the control inputs unchanged to the largest extent. Such a feature is relevant whenever dealing with, e.g., limited actuation since it guarantees that, even under model perturbations, the inputs do not deviate too much from their nominal values. This novel input sensitivity has been combined with the previously introduced notion of state sensitivity and validated both via monte-carlo simulations and experimentally with a unicycle robot in a large number of tests [1].

6.2.4. *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 in 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 computed 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 [22], [46].

6.2.5. *Strategies for Crowd Simulation Agents*

Participants: Wouter Van Toll, Julien Pettré.

This research activity is dedicated to the simulation of crowds based on microscopic approaches. In such approaches, agents move according to local models of interactions that give them the capacity to adjust to the motion of neighbor agents. These purely local rules are not sufficient to produce high-quality long term trajectories through their environment. We provide agents with the capacity to establish mid-term strategies to move through their environment, by establishing a local plan based on their prediction of their surroundings and by verifying regularly this prediction remains valid. In the case validity is not checked, planning a new strategy is triggered [55].

6.2.6. *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. We are 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 [36].

6.2.7. *Robot-Human Interactions during Locomotion*

Participants: Javad Amirian, Fabien Grzeskowiak, Marie Babel, 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. This year, we have delivered techniques for the short term prediction of human locomotion trajectories [34], [35] and robot-human collision avoidance [39].

6.2.8. Visual Servoing for Cable-Driven Parallel Robots

Participant: François Chaumette.

This study is done in collaboration with IRT Jules Verne (Zane Zake, Nicolo Pedemonte) and LS2N (Stéphane Caro) in Nantes (see Section 7.2.2). It is devoted to the analysis of the robustness of visual servoing to modeling and calibration errors for cable-driven parallel robots. The modeling of the closed loop system has been derived, from which a Lyapunov-based stability analysis allowed exhibiting sufficient conditions for ensuring its stability. Experimental results have validated the theoretical results obtained and shown the high robustness of visual servoing for this sort of robots [30], [56].

6.2.9. Visual Exploration of an Indoor Environment

Participants: Benoît Antoniotti, Eric Marchand, François Chaumette.

This study is done in collaboration with the Creative company in Rennes (see Section 6.2.9). It is devoted to the exploration of indoor environments by a mobile robot, Pepper typically (see Section 5.4.2) for a complete and accurate reconstruction of the environment. The exploration strategy we are currently developing is based on maximizing the entropy generated by a robot motion.

6.2.10. Deformation Servoing of Soft Objects

Participant: Alexandre Krupa.

Nowadays robots are mostly used to manipulate rigid objects. Manipulating deformable objects remains challenging due to the difficulty of accurately predicting the object deformations. This year, we developed a model-free deformation servoing method able to do an online estimation of the deformation Jacobian that relates the motion of the robot end-effector to the deformation of a manipulated soft object. The first experimental results are encouraging since they showed that our model-free visual servoing approach based on online estimation provides similar results than a model-based approach based on physics simulation that requires accurate knowledge of the physical properties of the object to deform. This approach has been recently submitted to the ICRA'20 conference.

6.2.11. Multi-Robot Formation Control

Participant: Paolo Robuffo Giordano.

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 several previous works we have addressed the problem of coordinating a team of quadrotor UAVs equipped with onboard sensors (such as distance sensors or cameras) for cooperative localization and formation control under the rigidity framework. In [9] an interesting interplay between the rigidity formalism and notions of parallel robotics has been studied, showing how well-known tools from the parallel robotics community can be applied to the multi-robot case, and how these tools can be used for characterizing the stability and singularities of the typical formation control/localization algorithms.

In [17], the problem of distributed leader selection has been addressed by considering agents with a second-order dynamics, thus closer to physical robots that have some unavoidable inertia when moving. This work has extended a previous strategy developed for a first-order case and ported it to the second-order: the proposed algorithm is able to periodically select at runtime the 'best' leader (among the neighbors of the current leader) for maximizing the tracking performance of an external trajectory reference while maintaining a desired formation for the group. The approach has been validated via numerical simulations.

6.2.12. Coupling Force and Vision for Controlling Robot Manipulators

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

The goal of this 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. 5.4.4), 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.

Towards this goal, this year we have considered the problem of identification of the dynamical model for the Panda robot [18], by suitably exploiting tools from identification theory. The identified model has been validated in numerous tests on the real robot with very good results and accuracy. A special feature of the model is the inclusion of a (realistic) friction term that accounts well for joint friction (a term that is usually neglected in dynamical model identification).

6.2.13. Subspace-based visual servoing

Participant: Eric Marchand.

To date most of visual servoing approaches have relied on geometric features that have to be tracked and matched in the image. Recent works have highlighted the importance of taking into account the photometric information of the entire images. This leads to direct visual servoing (DVS) approaches. The main disadvantage of DVS is its small convergence domain compared to conventional techniques, which is due to the high non-linearities of the cost function to be minimized. We proposed to project the image on an orthogonal basis (PCA) and then servo on either images reconstructed from this new compact set of coordinates or directly on these coordinates used as visual features [23]. In both cases we derived the analytical formulation of the interaction matrix. We show that these approaches feature a better behavior than the classical photometric visual servoing scheme allowing larger displacements and a satisfactory decrease of the error norm thanks to a well modelled interaction matrix.

6.2.14. Wheelchair Autonomous Navigation for Fall Prevention

Participants: Solenne Fortun, Marie Babel.

The Prisme project (see Section 8.1.4) 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 finalized the related control framework based on sensor-based servoing principles. We validated the proposed solution through usage tests within the Rehabilitation Center of Pôle Saint Hélier (Rennes).

6.3. Haptic Cueing for Robotic Applications

6.3.1. Wearable Haptics

Participants: Marco Aggravi, Claudio Pacchierotti.

We worked on developing a novel modular wearable finger interface for cutaneous and kinesthetic interaction [11], shown in Fig. 9. It is composed of a 3-DoF fingertip cutaneous device and a 1-DoF finger kinesthetic exoskeleton, which can be either used together as a single device or separately as two different devices. The 3-DoF fingertip device is composed of a static body and a mobile platform. The mobile platform is capable of making and breaking contact with the finger pulp and re-angle to replicate contacts with arbitrarily oriented surfaces.

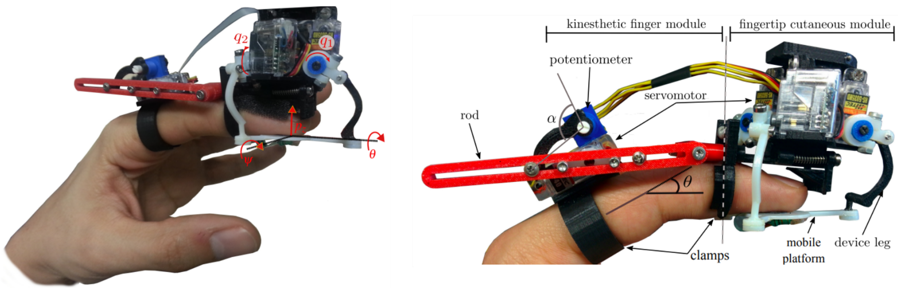


Figure 9. The proposed wearable device. It can provide both cutaneous feedback at the fingertip and kinesthetic feedback at the finger.

The 1-DoF finger exoskeleton provides kinesthetic force to the proximal and distal interphalangeal finger articulations using one servo motor grounded on the proximal phalanx. Together with the wearable device, we designed three different position, force, and compliance control schemes. We also carried out three human subjects experiments, enrolling a total of 40 different participants: the first experiment considered a curvature discrimination task, the second one a robotassisted palpation task, and the third one an immersive experience in Virtual Reality. Results showed that providing cutaneous and kinesthetic feedback through our device significantly improved the performance of all the considered tasks. Moreover, although cutaneous-only feedback showed promising performance, adding kinesthetic feedback improved most metrics. Finally, subjects ranked our device as highly wearable, comfortable, and effective.

On the same line of research, this year we guest edited a Special Issue on the IEEE Transactions on Haptics [26]. Thirteen papers on the topic have been published.

6.3.2. 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 (Sect. 8.3.5), 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.

In this respect, we started working on investigating the recognition of local shapes using mid-air ultrasound haptics [45]. We have presented a series of human subject experiments investigating important perceptual aspects related to the rendering of 2D shapes by an ultrasound haptic interface (the Ultrahaptics STRATOS platform). We carried out four user studies aiming at evaluating (i) the absolute detection threshold for a static focal point rendered via amplitude modulation, (ii) the absolute detection and identification thresholds for line patterns rendered via spatiotemporal modulation, (iii) the ability to discriminate different line orientations, and (iv) the ability to perceive virtual bumps and holes.

Our results show that focal point detection thresholds are situated around 560Pa peak acoustic radiation pressure, with no evidence of effects of hand movement on detection. Line patterns rendered through spatiotemporal modulation were detectable at lower pressures, however their shape was generally not recognized as a line below a similar threshold of approx. 540Pa peak acoustic radiation pressure. We did not find any significant effect of line orientation relative to the hand both in terms of detection thresholds and in terms of correct identification of line orientation.

6.3.3. Tangible objects in VR and AR

Participant: Claudio Pacchierotti.

Still in the framework of the H-Reality project (Sect. 8.3.5), we studied the role of employing simple tangible objects in VR and AR scenarios, to improve the illusion of telepresence in these environments. We started by investigating the role of haptic sensations when interacting with tangible objects. Tangible objects are used in Virtual Reality to provide human users with distributed haptic sensations when grasping virtual objects. To achieve a compelling illusion, there should be a good correspondence between the haptic features of the tangible object and those of the corresponding virtual one, i.e., what users see in the virtual environment should match as much as possible what they touch in the real world. For this reason, we aimed at quantifying how similar tangible and virtual objects need to be, in terms of haptic perception, to still feel the same [40]. As it is often not possible to create tangible replicas of all the virtual objects in the scene, it is indeed important to understand how different tangible and virtual objects can be without the user noticing. Of course, the visuohaptic perception of objects encompasses several different dimensions, including the object's size, shape, mass, texture, and temperature. We started by addressing three representative haptic features - width, local orientation, and curvature, - which are particularly relevant for grasping. We evaluated the just-noticeable difference (JND) when grasping, with a thumb-index pinch, a tangible object which differ from a seen virtual one on the above three important haptic features. Results show JND values of 5.75%, 43.8%, and 66.66% of the reference shape for the width, local orientation, and local curvature features, respectively.

As we mentioned above, for achieving a compelling illusion during interaction in VR, there should be a good correspondence between what users see in the virtual environment and what they touch in the real world. The haptic features of the tangible object should – up to a certain extent – match those of the corresponding virtual one. We worked on an innovative approach enabling the use of few tangible objects to render many virtual ones [41]. Toward this objective, we present an algorithm which analyses different tangible and virtual objects to find the grasping strategy best matching the resultant haptic pinching sensation. Starting from the meshes of the considered objects, the algorithm guides users towards the grasping pose which best matches what they see in the virtual scene with what they feel when touching the tangible object. By selecting different grasping positions according to the virtual object to render, it is possible to use few tangible objects to render multiple virtual ones. We tested our approach in a user study. Twelve participants were asked to grasp different virtual objects, all rendered by the same tangible one. For every virtual object, our algorithm found the best pinching match on the tangible one, and guided the participant toward that grasp. Results show that our algorithm was able to well combine several haptically-salient object features to find corresponding pinches between the given tangible and virtual objects. At the end of the experiment, participants were also asked to guess how many tangible objects were used during the experiment. No one guessed that we used only one, proof of a convincing experience.

6.3.4. Wearable haptics for an Augmented Wheelchair Driving Experience

Participants: Louise Devigne, François Pasteau, Marco Aggravi, Claudio Pacchierotti, Marie Babel.

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 then envisaged the use of wearable vibrotactile haptics, i.e. two haptic armbands, each composed of four evenly-spaced vibrotactile actuators. With respect to other available solutions, our approach provides rich navigation information while always leaving the patient in control of the wheelchair motion. We then conducted experiments with volunteers who experienced wheelchair driving in conjunction with the use of the armbands to provide drivers with information either on the presence of obstacles. Results show that providing information on closest obstacle position improved significantly the safety of the driving task (least number of collisions). This work is jointly conducted in the context of ADAPT project (Sect. 8.3.6) and ISI4NAVE associate team (Sect. 8.4.1.1).

6.4. Shared Control Architectures

6.4.1. Shared Control for Remote Manipulation

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

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 the main tools to design complex but intuitive robotic teleoperation system, 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 system, which can easily and rapidly change the division of roles between the user and autonomous controller.

Along this general line of research, during this year we gave the following contributions:

- in [51] we proposed a shared control algorithm for remote telemanipulation of redundant robots able to fuse the task-prioritized control architecture (for handling the concurrent realization of multiple tasks) with haptic guidance techniques. In particular, we developed a suitable passivity-preserving strategy based on energy tanks for always guaranteeing stability despite the possible presence of autonomous tasks that could generate an increase of energy during operation. The approach has been validated with extensive simulative results in a realistic environment.
- in [6] we have considered a shared control algorithm for telemanipulation that embeds the presence of a grasping planner for guiding the operator towards suitable grasping poses. The operator retains control of the end-effector motion and eventual grasping location, but she/he is assisted by the autonomy (via force cues) in navigating towards good grasps, as classified by the grasping planner that takes as input a RGBD image of the scene and computes a set of grasping poses along the object contour.
- in [50] we have presented two haptic shared-control approaches for robotic cutting. They are designed to assist the human operator by enforcing different nonholonomic-like constraints representative of the cutting kinematics. To validate this approach, we carried out a human-subject experiment in a real cutting scenario. We compared our shared-control techniques with each other and with a standard haptic teleoperation scheme. Results show the usefulness of assisted control schemes in complex applications such as cutting.

6.4.2. Teleoperation of Flexible Needle with Haptic Feedback and Ultrasound Guidance

Participants: Jason Chevrie, Alexandre Krupa, Marie Babel.

Needle insertion procedures under ultrasound guidance are commonly used for diagnosis and therapy. This kind of intervention can greatly benefit from robotic systems to improve their accuracy and success rate. In the past years, we have developed a robotic framework dedicated to 3D steering of beveled-tip flexible needle in order to autonomously reach a desired target in the tissues by ultrasound visual servoing using a 3D ultrasound probe. This year we have proposed a real-time semi-automatic teleoperation framework that enables the user to directly control the trajectory of the needle tip during its insertion via a haptic interface [38]. The framework enables the user to intuitively guide the trajectory of the needle tip in the ultrasound 3D volume while the controller handles the complexity of the 6D motion that needs to be applied to the needle base. A mean targeting accuracy of 2.5 mm has been achieved in gelatin phantoms and different ways to provide the haptic feedback as well as different levels of control given to the user on the tip trajectory have been compared. Limiting the user input to the insertion speed while automatically controlling the trajectory of the needle tip seems to provide a safer insertion process, however it may be too constraining and can not handle situations where more control over the tip trajectory is required, for example if unpredicted obstacles need to be avoided. On the contrary, giving the full control of the 3D tip velocity to the user and applying a haptic feedback to guide the user toward the target proved to maintain a low level of needle bending and tissue deformation.

6.4.3. Needle Comanipulation with Haptic Guidance

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 7.2.3). At the difference of our work presented in Section 6.4.2 where a robotic system is used to steer the needle, we propose in this study another way of assistance where the needle is collaboratively manipulated by the physician and a haptic device. The principle of our approach is to provide haptic cue feedback to the clinician in order to help him during his manual gesture [43]. 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. The haptic guides rely on the position and orientation errors between the needle, the entry point and the desired angle of incidence toward the target, which are computed from the measurements provided by an electromagnetic tracker. Each of the guide implements a different Guiding Virtual Fixture producing haptic cues that attract the needle towards a point or a trajectory in space with different force feedback applied on the user's hand manipulating the needle. A two-step evaluation was conducted to assess the performance and ergonomy of each haptic guide, and compare them to the unassisted reference gesture. The first evaluation stage [44] involved two physicians both experts in needle manipulation at Rennes University Hospital. The performance results showed that, compared to the unassisted gesture, the positioning accuracy was enhanced with haptic guidance. The second evaluation stage [43] was a user study with twelve participants. From this second study it results that the most constraining guide allows to perform the gesture with the best accuracy, lower time duration and highest level of ergonomy.

6.4.4. 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 navigating on sidewalks, negotiating curbs or dealing with uneven grounds. Indeed, differences of elevation have been reported to be one of the most challenging environmental barrier to negotiate, with tipping and falling being the most common accidents power wheelchair users encounter. It is thus our 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 shared-control algorithm which provides assistance while navigating with a wheelchair in an environment consisting of negative obstacles. We designed a dedicated sensor-based control law allowing trajectory correction while approaching negative obstacles e.g. steps, curbs, descending slopes. This shared control method takes into account the humanin-the loop factor. In this study, our solution the ability of our system to ensure a safe trajectory while navigating on a sidewalk is demonstrated through simulation, thus providing a proof-of-concept of our method [42].

6.4.5. Wheelchair-Human Interactions during crossing situations

Participants: Marie Babel, Julien Pettré.

Designing smart powered wheelchairs requires to better understand interactions between walkers and such vehicles. We focus on collision avoidance task between a power wheelchair (fully operated by a human) and a walker, where the difference in the nature of the agents (weight, maximal speed, acceleration profiles) results into asymmetrical physical risk in case of a collision, for example due to the protection power wheelchair provides to its driver, or the higher energy transferred to the walker during head-on collision.

We then conducted experiments with Results show that walkers set more conservative strategies when interacting with a power wheelchair. These results can then be linked to the difference in the physical characteristics of the walkers and power wheelchairs where asymmetry in the physical risks raised by collisions influence the strategies performed by the walkers in comparison with a similar walker-walker situation. This gives interesting insights in the task of modeling such interactions, indicating that geometrical terms are not sufficient to explain behaviours, physical terms linked to collision momentum should also be considered [49][62].

6.4.6. Multisensory power wheelchair simulator

Participants: Guillaume Vailland, Louise Devigne, François Pasteau, Marie Babel.

Power wheelchair driving is a challenging task which requires good visual, cognitive and visuo-spatial abilities. Besides, a power wheelchair can cause material damage or represent a danger of injury for others or oneself if not operated safely. Therefore, training and repeated practice are mandatory to acquire safe driving skills to obtain power wheelchair prescription from therapists. However, conventional training programs may reveal themselves insufficient for some people with severe impairments. In this context, Virtual Reality offers the opportunity to design innovative learning and training programs while providing realistic wheelchair driving experience within a virtual environment. We then proposed a user-centered design of a multisensory power wheelchair simulator [59][58]. This simulator addresses classical virtual experience drawbacks such as cybersickness and sense of presence by combining 3D visual rendering, haptic and vestibular feedback. It relies on a modular and versatile workflow enabling not only easy interfacing with any virtual display, but also with any user interface such as wheelchair controllers or feedback devices. First experiments with able-bodied people shown that vestibular feedback activation increases the Sense of Presence and decreases cybersickness [54].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. 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 (see Sect. 5.4.3). Each module is rent 40 days during a 3-year period in the context of the IRT B<>com NeedleWare project (see Section 7.2.3).

7.2. Bilateral Grants with Industry

7.2.1. Creative

Participants: Benoît Antoniotti, François Chaumette, Eric Marchand.

No Inria Rennes 13996, duration: 36 months.

This project funded by Creative started in March 2019. It supports Benoît Antoniotti's Ph.D. about visual exploration (see Section 6.2.9).

7.2.2. IRT JV Perform

Participant: François Chaumette.

No Inria Rennes 14049, duration: 36 months.

This project funded by IRT Jules Verne in Nantes started in January 2018. It is achieved in cooperation with Stéphane Caro from LS2N in Nantes to support Zane Zake's Ph.D. about visual servoing of cable-driven parallel robots (see Section 6.2.8).

7.2.3. 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 6.4.3). This year, we published [43] [44] in the scope of this project.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. SAD WH-DRONE

Participants: Marco Aggravi, Claudio Pacchierotti.

no CNRS Rennes 181089, duration: 24 months.

This project funded by the Brittany council started in January 2019. It supports in part Marco Aggravi's research on using wearable interfaces for flying swarms of drones.

8.1.2. 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 supports the activities related to the teleoperation of drones (quadrotor UAVs) using wearable haptics interfaces.

8.1.3. 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.

8.1.4. Prisme

Participants: Solenne Fortun, François Pasteau, Marie Babel.

no Insa Rennes 2017-0004, duration: 36 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 addressed (see Section 6.2.14).

8.1.5. Silver Connect

Participant: Marie Babel.

no Insa Rennes 2018-0076, duration: 34 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.

8.1.6. Cartam

Participants: Noura Neji, Fabien Spindler, François Chaumette.

no Inria 13954 and 14041, duration: 36 months.

This project started in January 2019 and is supported by Brittany region and FEDER. It is managed by Triskalia with Unilet, Copeeks, Neotec Vision, Rainbow group, and our start-up Dilepix. It aims at designing a vision system able to detect adventices in a field. We are in charge of tracking the adventices once they are detected and of building a mosaic of the field for locating them.

8.2. National Initiatives

8.2.1. 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 Inria (Chorale group in Sophia-Antipolis and Rainbow). The project is focused on robust long-term mapping of urban environments. Map building consists in the acquisition of a textured 3-D model of urban environment, and automatic semantic labelling of the environment features (roads, buildings, cars, etc.). From this model, an optimal representation is generated and made available in the cloud, in the form of a network of RGB-D-L spheres storing photometry, geometry (depth) and object labels. Mobile agents are able to determine their position and navigate in the sphere graph using dense matching. Agents upload significant environment changes to the sphere server in cloud, for map update purposes.

8.2.2. ANR Sesame

Participant: François Chaumette.

no Inria 13722, duration: 48 months.

This project started in January 2019. It involves a consortium managed by LS2N (Nantes) with LIP6 (Paris) and Rainbow group. It aims at analysing singularity and stability issues in visual servoing.

8.2.3. 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 in 2015.

8.3. European Initiatives

FP7 & H2020 Projects

8.3.1. 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: A huge amount of debris have progressively been generated since the beginning of the space era. Most of the objects launched into space are still orbiting the Earth and today these objects and their by-products represent a threat both in space and on Earth. In Space, debris lead to collisions and therefore to damages to operational satellites. For both issues, a credible solution has emerged over the recent years: actively removing heavy debris objects by capturing them and then either disposing them by destructive re-entry in Earth atmosphere or disposing them in graveyard orbits. The RemoveDEBRIS project aimed to demonstrate key technologies for ADR in three main domains by performing in-orbit demonstrations representative of an ADR mission. The specific key technologies that have been demonstrated as part of this project are: (i) Capture technologies such as nets and harpoons (ii) De-orbiting technologies such as electric propulsion and drag augmentation (iii) Proximity Rendezvous operations technologies based on vision-based navigation. The technology demonstrations has been carried in orbit using a micro satellite test-bed, a world's first. The micro satellite has carried the ADR payloads together with two deployable nanosatellites (CubeSats). Through a series of operations, the nanosatellites have been ejected, re-captured, inspected and de-orbited, thereby demonstrating the ADR key technologies [16], [8], [7]. Our goal in this long project was to develop and validate model-based tracking algorithms on images acquired during the actual space debris removal mission [47].

8.3.2. H2020 ICT Comanoid

Participants: Fabien Spindler, François Chaumette.

Title: Multi-contact Collaborative Humanoids in Aircraft Manufacturing

Programme: H2020

Duration: January 2015 - February 2019

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 investigated 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 was 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 suggested 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 aimed at assessing clearly how far the state-of-the-art stands from such novel technologies. In particular the project focused on implementing a real-world humanoid robotics solution using the best of research and innovation. The main challenge was 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 [21].

8.3.3. H2020 ICT CrowdBot

Participants: Javad Amirian, Fabien Grzeskowiak, Solenne Fortun, Marie Babel, Julien Pettré, Fabien Spindler.

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.

8.3.4. H2020 ICT PRESENT

Participants: Adèle Colas, Alberto Jovane, Claudio Pacchierotti, Julien Pettré.

Title: Photoreal REaltime Sentient ENTity

Programme: H2020

Duration: Sep 2019 - Aug 2022

Coordinator: Univ Pompeu Fabra (Spain)

Partners: The Framestore Ltd (UK), Cubic Motion Ltd (UK), InfoCert Spa (Italy), Brainstorm Multimedia S.L. (ES), Creative Workers - Creatieve Werkers VZW (Belgium), Universitaet Augsburg (Germany), Inria (France)

Inria contact: Julien Pettré

Abstract: PRESENT is a three-year Research and Innovation project to create virtual digital companions—embodied agents—that look entirely naturalistic, demonstrate emotional sensitivity, can establish meaningful dialogue, add sense to the experience, and act as trustworthy guardians and guides in the interfaces for AR, VR and more traditional forms of media.

There is no higher quality interaction than the human experience when we use all our senses together with language and cognition to understand our surroundings and—above all—to interact with other people. We interact with today's Ïntelligent Personal Assistantsprimarily by voice; communication is episodic, based on a request-response model. The user does not see the assistant, which does not take advantage of visual and emotional clues or evolve over time. However, advances in the real-time creation of photorealistic computer generated characters, coupled with emotion recognition and behaviour, and natural language technologies, allow us to envisage virtual agents that are realistic in both looks and behaviour; that can interact with users through vision, sound, touch and movement as they navigate rich and complex environments; converse in a natural manner; respond to moods and emotional states; and evolve in response to user behaviour.

PRESENT will create and demonstrate a set of practical tools, a pipeline and APIs for creating realistic embodied agents and incorporating them in interfaces for a wide range of applications in entertainment, media and advertising.

8.3.5. H2020 FET-OPEN H-Reality

Participants: Claudio Pacchierotti, Paolo Robuffo Giordano, François Chaumette.

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), CNRS (France), 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. Rainbow is involved in H-Reality in cooperation with Anatole Lécuyer and Maud Marchal from the Hybrid group.

Collaborations in European Programs, Except FP7 & H2020

8.3.6. *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 Hélier (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.

Collaborations with Major European Organizations

8.3.7. *ANR Opmops*

Participants: Florian Berton, Julen 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.

8.3.8. 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 Ocean (Norway)

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

Abstract: This project was granted by the Norwegian Government. Its main objective was to develop novel concepts and methods for flexible and sustainable food processing in Norway. In the scope of this project, the Rainbow group was involved for visual tracking and visual servoing of generic and potentially deformable objects (see Section 6.1.1 and Section 6.1.2). This year, we published [52], [53] in the scope of this project.

8.3.9. GentleMAN

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

Project acronym: GentleMAN

Project title: Gentle and Advanced Robotic Manipulation of 3D Compliant Objects

Duration: August 2019 - December 2023

Coordinator: Sintef Ocean (Norway)

Other partners: NTNU (Norway), NMBU (Norway), MIT (USA) and QUT (Australia).

Abstract: This project is funded by the Norwegian Government. Its main objective is to develop a novel learning framework that uses visual, force and tactile sensing to develop new multi-modal learning models, interfaced with underlying robot control, for enabling robots to learn new and advanced skills for the manipulation of 3D compliant objects. In the scope of this project, the Rainbow group is involved in the elaboration of new approaches for visual tracking of deformable objects, active vision and visual servoing for deforming soft objects into desired shapes.

8.4. International Initiatives

8.4.1. Inria Associate Teams Not Involved in an Inria International Labs

8.4.1.1. ISI4NAVE

Title: Innovative Sensors and adapted Interfaces for assistive NAVigation and pathology Evaluation

International Partner (Institution - Laboratory - Researcher):

University College London (United Kingdom) - Aspire CREATe - Tom Carlson

Start year: 2019

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

Using a wheelchair allows people with disability to compensate a loss of mobility. However only 5 to 15% of the 70 million people worldwide who require a wheelchair have access to this type of technical aid. In particular, visual, visuo-spatial and/or cognitive impairments can alter the ability of an individual to independently operate a wheelchair safely.

This project focuses then on two main complementary objectives:

1. to compensate both sensorimotor disabilities and cognitive impairments by designing adapted interfaces,
2. to enhance the driving experience and to bring a new tool for rehabilitation purposes by defining efficient physical Human-Robot Interaction.

In order to ensure a widespread use of robotic systems, innovative interfaces, enabling relevant feedback (medically validated), constitute a major challenge. Trajectory corrections, obtained thanks to an assistance module, will have to be perceived by the user by means of sensitive (visual, tactile...) feedback that will have to be easily adapted to the pathology. Conversely, user interaction with the robotic system can be interpreted to control the wheelchair. Designing such systems require a multidisciplinary study, including medical data collection and analysis.

In our preliminary works, we demonstrated the relevance of share control frameworks. The scope of this new ISI4NAVE Associate Team is then to provide advanced and innovative solutions for controlling wheelchair as well as providing appropriate and relevant feedback to users.

8.4.2. Participation in Other International Programs

8.4.2.1. 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, Alexander Oliva received a grant to participate to the 2019 Robotic Vision Summer School in Kioloa (New South Wales) and spent a 1-week visit at QUT in March 2019.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events: Organisation

9.1.1.1. General Chair, Scientific Chair

- Marie Babel was the Scientific Chair and the General co-chair of the workshop “Robotique de la marche” organized in Inria Rennes on December 13th 2019.

9.1.1.2. Member of the Organizing Committees

- P. Robuffo Giordano co-organized with F. Schiano and D. Floreano (EPFL) the Workshop on “Aerial Swarms” at the 2019 International Conference on Intelligent Systems and Robots, Macau, China

9.1.2. Scientific Events: Selection

9.1.2.1. Chair of Conference Program Committees

- Paolo Robuffo Giordano: Program Co-Chair of MRS 2019
- François Chaumette: Program Co-Chair of ICRA 2020 to be held in Paris in June 2020.

9.1.2.2. Member of the Conference Program Committees

- Claudio Pacchierotti: Eurohaptics (Associate Editor), World Haptics (Associate Editor), ICRA 2020 (Associate Editor), Demonstrations Co-Chair, IEEE Haptics Symposium (HAPTICS) 2020
- Paolo Robuffo Giordano: ICRA 2020 (Associate Editor), RSS 2019 (Area Chair)
- Eric Marchand: ICRA 2020 (Associate Editor)
- Julien Pettré: IEEE Virtual Reality 2019, ACM Motion and Interactions in Games 2019, ACM Symposium on Computer Animation

9.1.2.3. Reviewer

- Alexandre Krupa: IROS 2019 (1), ICRA 2020 (1)
- Eric Marchand: IROS 2019 (1), ICRA 2019 (2), ICRA 2020 (1)
- Marie Babel: ICRA 2020 (4), SMC 2019 (1)
- Paolo Robuffo Giordano: ICRA 2020 (2)
- François Chaumette: ICRA 2020 (1), CDC 2019 (1), RoMoCo 2019 (1)

9.1.3. Journal

9.1.3.1. Member of the Editorial Boards

- Paolo Robuffo Giordano is Editor for the IEEE Transactions on Robotics since January 2019
- Alexandre Krupa was Associate Editor of IEEE Robotics and Automation Letters (RA-L) (until June 2019) and is currently Associate Editor for the IEEE Transactions on Robotics (since July 2019)
- Eric Marchand is a Senior Editor of IEEE Robotics and Automation Letters (RA-L) and an Editor for Interstices)i(
- François Chaumette: Editor of the IEEE Transactions on Robotics, Editorial Board of the Int. Journal of Robotics Research, Editorial Board of the Springer Tracts in Advanced Robotics, Board Member of the Springer Encyclopedia of Robotics.
- Julien Pettré is Associate Editor for the Wiley's Computer Graphics Forum, and Associate Editor for the Wiley's Computer Animation and Virtual Worlds

9.1.3.2. Reviewer - Reviewing Activities

- Vincent Drevelle: ActaCybernetica
- Eric Marchand: IEEE RA-L (2)
- Marie Babel: IEEE RA-L (1)
- Paolo Robuffo Giordano: IJRR (1), IEEE RA-L (1), IEEE T-CST (2), IEEE T-RO (2)
- François Chaumette: IEEE Trans. on Industrial Electronics (2), IEEE RA-L (1), Acta Astronautica (1)
- Claudio Pacchierotti: RAL (1), IJHCS (5), TOH (7), JMRR (1), ICRA (4), TIE (2), TVCG (1), Frontiers in Robotics and AI (2), THMS (1), Presence (1), Scientific Reports (1)

9.1.4. Invited Talks

- Paolo Robuffo Giordano:
  - "Human-assisted Robotics", Robotics and Mechatronics lab, University of Twente, Netherlands, October 2019
  - "Collective Control, State Estimation and Human Interaction for Quadrotors in Unstructured Environments", Technoférence, Images et Réseaux, Rennes, October 2019
  - "Human-assisted Robotics", Robotics Research Jam Session, Univ. of Pisa, Italy, April 2019
- Claudio Pacchierotti:
  - with A. M. Okamura, "Learnings from cross-functional work on skin stretch haptics." Workshop "Cross-functional collaboration between engineering & perception researchers" at WHC Conference, Tokyo, Japan, 2019.
  - "Cutaneous haptic technologies for robotics and immersive environments." Cirrus Logic, Edinburgh, United Kingdom, 2019.
  - "Virtual Reality and Robotics for Industry 4.0." University of Aarhus, Herning, Denmark, 2019.
- Marie Babel:
  - "Simulation virtuelle et retour haptique du mouvement : une expérience de conduite réaliste immersive", Séminaire d'hiver de l'IFRATH, Paris, January 2019
  - "Fauteuil roulant intelligent : croiser les regards (académiques et cliniques)", Technoférence, Images et Reseaux, January 2019
- François Chaumette:

  - Plenary talk on “Geometric and end-to-end robot vision-based control” at 12th Int. Workshop on Robot Motion and Control (RoMoCo 2019), Poznan, Poland, July 2019 [33].
  - “Sensor-based Control”, GdR Robotics Winter School : Robotics Principia, Sophia-Antipolis, January 2019.
- Fabien Spindler:
  - “Avancées en vision pour la saisie et la manipulation”, Journée GT3 du GDR robotique, ISIR, Paris, Juin 2019

9.1.5. Leadership within the Scientific Community

- Claudio Pacchierotti is the Chair of the IEEE Technical Committee on Haptics and the Secretary of the Eurohaptics Society.
- François Chaumette is a member of the Scientific Council of RTE Vedecom, ImVIA lab in Dijon and Le Creusot, and a founding member of the Scientific Council of the “GdR Robotique”.

9.1.6. Scientific Expertise

- Paolo Robuffo Giordano was reviewer for evaluating proposals of the ANR (French National Research Agency), Mitacs (Canada), SNSF (Swiss National Science Foundation), MIUR (Italian National Research Agency), and the EU commission (ERC Consolidator Grants)
- Claudio Pacchierotti was reviewer for evaluating proposals of the European Science Foundation (ESF).
- Fabien Spindler was a member of the HCERES evaluation committee of URIA, the laboratory of the Ecole des Mines de Douai, the DTIS laboratory of Onera and the LISTIC in Annecy.
- Marie Babel serves as an expert for the International Mission of the French Research Ministry (MEIRIES) - Campus France (about 30 expertises per year). She was also reviewer for evaluating proposals of the ANR (French National Research Agency)
- François Chaumette served for the fourth (and last) time as Panel Member of the PE7 ERC Consolidator Grants. He also served as member of IEEE RAS Pioneer Award Evaluation Panel and IEEE RAS Awards Evaluation Panel. He was a panel member of the 2019 ICREA Academia program (similar to IUF for Catalonia). Finally, he served in the jury for the Inria research positions (CR2) available for the Inria Rennes-Bretagne Atlantique centre.

9.1.7. Research Administration

- Alexandre Krupa is a member of the CUMIR (“Commission des Utilisateurs des Moyens Informatiques pour la Recherche”) of Inria Rennes-Bretagne Atlantique, he 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 is the head of "Digital Signals and Images, Robotics" department at IRISA.
- 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. Since December 2019, he is a member of the Inria COERLE committee (in charge of the ethical aspects of all Inria research).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Marie Babel:

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

Master INSA1: “Concepts de la logique à la programmation”, 20 hours, L3, INSA Rennes

Master INSA1: “Langage C”, 12 hours, L3, INSA Rennes

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

Master INSA1: “Practical studies”, 16 hours, L3, INSA Rennes

Master INSA2: “Image analysis”, 26 hours, M1, INSA Rennes

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

François Chaumette:

Master SISEA: “Robot Vision”, 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 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”, 42 hours, L1, Université de Rennes 1

Master Elec: “Electronics project”, 16 hours, M1, Université de Rennes 1

Portail Info-Elec: “Discovering programming and electronics”, 22 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 FIP TIC-Santé: “Ultrasound visual servoing”, 6 hours, M2, Télécom Physique Strasbourg

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, Unviersité de Rennes 1

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

9.2.2. Supervision

- Ph.D. in progress: Agniva Sengupta, “Visual tracking of deformable objects with RGB-D camera”, started in January 2017, supervised by Alexandre Krupa and Eric Marchand
- Ph.D. in progress: Xavier De Tinguy de la Girouliére, “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: 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: Romain Lagneau (Hybrid group), “Control of soft object deformation by visual servoing”, started in October 2017, supervised by Alexandre Krupa and Maud Marchal (Hybrid group)
- Ph.D. in progress: Florian Berton, “Gaze analysis for crowd behaviours study”, started in October 2017, supervised by Anne-Hélène Olivier (MimeTIC group), Ludovic Hoyet (MimeTIC group) and Julien Pettré
- 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: Javad Amirian, “Crowd motion prediction for robot navigation in dense crowds”, started in January 2018, supervised by Jean-Bernard Hayet (CIMAT, Guana) and Julien Pettré
- 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 (MimeTIC group)
- 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: Ketty Favre “Lidar-based localization”, started in October 2018, supervised by Eric Marchand, Muriel Pressigout and Luce Morin (IMAGE group)
- 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: Guillaume Vailland, “Outdoor wheelchair assisted navigation: reality versus virtuality”, started in November 2018, supervised by Marie Babel and Valérie Gouranton (Hybrid group)
- Ph.D. in progress: Benoît Antoniotti “Scene reconstruction and exploration”, started in March 2019, supervised by Eric Marchand, François Chaumette, and Antoine Lehuger (Creative)
- Ph.D. in progress: Pascal Brault, “Planification et optimisation de trajectoires robustes aux incertitudes paramétriques pour des taches robotiques fondées sur l’usage de capteurs”, started in September 2019, supervised by Paolo Robuffo Giordano and Quentin Delamare
- Ph.D. in progress: Alberto Jovane, “Modélisation de mouvements réactifs et comportements non verbaux pour la création d’acteurs digitaux pour la réalité virtuelle”, started in September 2019, supervised by Marc Christie (MimeTIC group), Claudio Pacchierotti, Ludovic Hoyet (MimeTIC group) and Julien Pettré
- Ph.D. in progress: Samuel Felton “Deep Learning for visual servoing”, started in October 2019, supervised by Eric Marchand and Elisa Fromont (Lacodam group)
- Ph.D. in progress: Mathieu Gonzalez “SLAM in time varying environment”, started in October 2019, supervised by Eric Marchand and Jérome Royan (IRT B<>COM)
- Ph.D. in progress: Adèle Colas, “Modélisation de comportements collectifs réactifs et expressifs pour la réalité virtuelle”, started in November 2019, supervised by Claudio Pacchierotti, Anne-Hélène Olivier, Ludovic Hoyet (MimeTIC group) and Julien Pettré
- Ph.D. defended: Salma Jiddi, “Photometric Registration of Indoor Real Scenes using an RGB-D Camera with Application to Mixed Reality", defended in January 2019, supervised by Eric Marchand [2]

- Ph.D. defended: Ide-Flore Kenmogne “Localisation ensembliste de drones à l’aide de méthodes par intervalles”, defended in March 2019, supervised by Eric Marchand and Vincent Drevelle [3]
- Ph.D. defended: Quentin Delamare, “Algorithmes d’estimation et de commande pour des quadrirotors en interaction physique avec l’environnement”, defended on December 2019, supervised by Paolo Robuffo Giordano and Antonio Franchi (LAAS) [1]
- Ph.D. defended: Axel Lopez Gandia, “Optical flow-based navigation algorithms for virtual humans”, defended on December 2019, supervised by Julien Pettré and François Chaumette [4]
- Ph.D. to be defended: Hadrien Gurnel “Needle comanipulation with haptic guidance for percutaneous interventions”, to be defended in January 2020, supervised by Alexandre Krupa, Maud Marchal (Hybrid group) and Laurent Launay (IRT B<>com)

9.2.3. Internships

- Alexandre Bonneau, ENS Rennes - Univ. Rennes 1, “Haptic rendering of virtual contacts in crowded environments”, supervised by J. Pettré
- Pascal Brault, ENS Rennes - Univ. Rennes 1, “Planning of Minimally Sensitive Trajectories for Mobile Robots”, supervised by Q. Delamare and P. Robuffo Giordano
- Valerio Paduani, Univ. of Rome “La Sapienza”, Italy, “Perception-Aware Human-Assisted Navigation of Mobile Robots on Persistent Trajectories”, supervised by M. Cognetti and P. Robuffo Giordano
- Giulia Matarese, Univ. of Pisa, Italy, “Caring about the human operator: haptic shared control for enhanced user comfort in robotic telemanipulation”, supervised by C. Pacchierotti and P. Robuffo Giordano
- Riccardo Arciulo, Univ. of Rome “La Sapienza”, Italy, “Novel Solution For Human-Robot physical interaction in collaborative tasks”, supervised by C. Pacchierotti and P. Robuffo Giordano
- Ahmed Elsherif, École Centrale de Nantes (EMARO), “Shared control of drones with wearable haptic interfaces”, supervised by C. Pacchierotti and M. Aggravi
- Daniel Lemos Estima, University of Twente, “Integration between a grounded haptic interface and a robot-assisted flexible needle insertion system”, supervised by C. Pacchierotti
- David Steeven Villa Salazar, Univ. Federal do Rio Grande do Sul, “Development of Virtual Reality scenes rendered using ultrasound and vibrotactile haptic interfaces”, supervised by C. Pacchierotti
- Samuel Felton, INSA Rennes - Univ. Rennes 1, “Deep Learning for Visual Servoing”, supervised by E. Marchand
- Gatien Gaumerais, ESIR 2 - Univ. Rennes 1, “Visual-servoing with Parrot Bebop 2 drone”, supervised by F. Spindler
- Quentin Zanini, ENS - Univ. Rennes 1, “Design of a library of 3D shapes for haptic rendering using the ultrahaptics device”, supervised by C. Pacchierotti and M. Marchal (Hybrid group)

9.2.4. Juries

- Paolo Robuffo Giordano: Davide Bicego (Ph.D., member, LAAS, Toulouse)
- Julien Pettré: Jennifer Vandoni (Ph.D., member, Paris Saclay) and Maxime Garcia (Ph.D., reviewer, Grenoble Alpes)
- Eric Marchand: Maxime Rousselot (Ph.D. president, univ. de Rennes 1), Dmitry Kuzovkin (Ph.D. president, univ. de Rennes 1), Gilles Simon (HDR, reviewer, Univ. de Lorraine)
- Marie Babel: Lydia Habib (Ph.D., member, LAMIH, Université Polytechnique Hauts de France)
- François Chaumette: Eulalie Coevet (Ph.D., president, Inria Lille), Mateus Laranjeira (Ph.D., reviewer, Cosmer, Toulon), Brahim Tamadazte (HdR, reviewer, Femto, Besançon), Guillaume Caron (HdR, member, MIS, Amiens)

9.3. 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, 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, the power wheelchair simulator, and augmented reality applications. Some of these demonstrations are available as videos on VispTeam YouTube channel (https://www.youtube.com/user/VispTeam/videos).

9.3.1. Interventions

- François Pasteau participated to the Tech'in Vitré forum with an interview in March 2019.
- Solenne Fortun participated to the Societé de gérontologie de l'ouest et du centre (SGOC) congress with an interview in May 2019.
- Marie Babel animated an interactive session organized in Inria Rennes about "J'peux pas, j'ai informatique" on April 3rd, 2019 for secondary-school pupils.

10. Bibliography

Publications of the year

Doctoral Dissertations and Habilitation Theses

[1] Q. DELAMARE. *Algorithms for estimation and control of quadrotors in physical interaction with their environment*, Univ Rennes, Inria, CNRS, IRISA, France, December 2019, https://tel.archives-ouvertes.fr/tel-02410023

[2] S. JIDDI. *Photometric registration of indoor real scenes using an RGB-D camera with application to mixed reality*, Université Rennes 1, January 2019, https://tel.archives-ouvertes.fr/tel-02167109

[3] I.-F. KENMOGNE. *Set-membership localization of drones using interval methods*, Université de Rennes 1, March 2019, https://tel.archives-ouvertes.fr/tel-02405857

[4] A. LÓPEZ. *Optical flow-based navigation algorithms for virtual humans*, Université de Rennes 1, December 2019, https://tel.archives-ouvertes.fr/tel-02418923

Articles in International Peer-Reviewed Journals

[5] F. ABI-FARRAJ, B. HENZE, C. OTT, P. ROBUFFO GIORDANO, M. A. ROA. *Torque-Based Balancing for a Humanoid Robot Performing High-Force Interaction Tasks*, in "IEEE Robotics and Automation Letters", April 2019, vol. 4, n^o 2, pp. 2023-2030, (also presented at ICRA'19) [*DOI :* 10.1109/LRA.2019.2898041], https://hal.inria.fr/hal-02051454

[6] F. ABI-FARRAJ, C. PACCHIEROTTI, O. ARENZ, G. NEUMANN, P. ROBUFFO GIORDANO. *A Haptic Shared-Control Architecture for Guided Multi-Target Robotic Grasping*, in "IEEE Transactions on Haptics (ToH)", April 2019, pp. 1-16 [*DOI :* 10.1109/TOH.2019.2913643], https://hal.inria.fr/hal-02113206

[7] G. S. AGLIETTI, B. TAYLOR, S. FELLOWES, S. AINLEY, D. TYE, C. COX, A. ZARKESH, A. MAFFICINI, N. VINKOFF, K. BASHFORD, T. SALMON, I. RETAT, C. BURGESS, A. HALL, T. CHABOT, K. KANANI, A. PISSELOUP, C. BERNAL, F. CHAUMETTE, A. POLLINI, W. STEYN. *Survey Paper RemoveDEBRIS: An in-orbit demonstration of technologies for the removal of space debris*, in "Aeronautical Journal -New Series-", 2020, pp. 1-23 [*DOI :* 10.1017/AER.2019.136], https://hal.inria.fr/hal-02406580

[8] G. AGLIETTI, B. TAYLOR, S. FELLOWES, T. SALMON, I. RETAT, A. HALL, T. CHABOT, A. PISSELOUP, C. M. COX, A. ZARKESH, A. MAFFICINI, N. VINKOFF, K. BASHFORD, C. BERNAL, F. CHAUMETTE, A. POLLINI, W. STEYN. *The active space debris removal mission RemoveDebris. Part 2: in orbit operations*, in "Acta Astronautica", September 2019, pp. 1-16 [*DOI :* 10.1016/J.ACTAASTRO.2019.09.001], https://hal.inria.fr/hal-02286751

[9] S. BRIOT, P. ROBUFFO GIORDANO. *Physical Interpretation of Rigidity for Bearing Formations: Application to Mobility and Singularity Analyses*, in "Journal of Mechanisms and Robotics", April 2019, vol. 11, n^{o} 3, pp. 031006-1–031006-10 [*DOI :* 10.1115/1.4043050], https://hal.archives-ouvertes.fr/hal-02061643

[10] 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", 2019, vol. 14, n^{o} 2, pp. 321-333 [*DOI :* 10.1007/S11548-018-1887-3], https://hal.inria.fr/hal-01940752

[11] F. CHINELLO, M. MALVEZZI, D. PRATTICHIZZO, C. PACCHIEROTTI. *A modular wearable finger interface for cutaneous and kinesthetic interaction: control and evaluation*, in "IEEE Transactions on Industrial Electronics", January 2020, vol. 67, n^{o} 1, pp. 706-716 [*DOI :* 10.1109/TIE.2019.2899551], https://hal.inria.fr/hal-02021347

[12] N. CROMBEZ, E. M. MOUADDIB, G. CARON, F. CHAUMETTE. *Visual Servoing with Photometric Gaussian Mixtures as Dense Feature*, in "IEEE Transactions on Robotics", February 2019, vol. 35, n^{o} 1, pp. 49-63 [*DOI :* 10.1109/TRO.2018.2876765], https://hal.inria.fr/hal-01896859

[13] L. DEVIGNE, M. AGGRAVI, M. BIVAUD, N. BALIX, S. TEODORESCU, T. CARLSON, T. SPRETERS, C. PACCHIEROTTI, M. BABEL. *Power wheelchair navigation assistance using wearable vibrotactile haptics*, in "IEEE Transactions on Haptics (ToH)", January 2020, pp. 1-6 [*DOI :* 10.1109/TOH.2019.2963831], https://hal.inria.fr/hal-02428307

[14] L.-A. DUFLOT, R. REISENHOFER, B. TAMADAZTE, N. ANDREFF, A. KRUPA. *Wavelet and Shearlet-based Image Representations for Visual Servoing*, in "The International Journal of Robotics Research", April 2019, vol. 38, n^{o} 4, pp. 422-450 [*DOI :* 10.1177/0278364918769739], https://hal.archives-ouvertes.fr/hal-01735241

[15] P. ECORMIER-NOCCA, J. PETTRÉ, P. MEMARI, M.-P. CANI. *Image-based Authoring of Herd Animations*, in "Computer Animation and Virtual Worlds", 2019, vol. 30, n^{o} 3-4, pp. 1-11, forthcoming [*DOI :* 10.1002/CAV.1903], https://hal.inria.fr/hal-02127824

[16] J. FORSHAW, G. AGLIETTI, S. FELLOWES, T. SALMON, I. RETAT, A. HALL, T. CHABOT, A. PISSELOUP, D. TYE, C. BERNAL, F. CHAUMETTE, A. POLLINI, W. STEYN. *The active space debris removal mission RemoveDebris. Part 1: from concept to launch*, in "Acta Astronautica", 2019, pp. 1-19 [*DOI :* 10.1016/J.ACTAASTRO.2019.09.002], https://hal.inria.fr/hal-02286651

[17] A. FRANCHI, P. ROBUFFO GIORDANO, G. MICHIELETTO. *Online Leader Selection for Collective Tracking and Formation Control: the Second Order Case*, in "IEEE Transactions on Control of Network Systems", December 2019, vol. 6, n^o 4, pp. 1415-1425 [*DOI :* 10.1109/TCNS.2019.2891011], https://hal.laas.fr/hal-01964754

[18] C. GAZ, M. COGNETTI, A. OLIVA, P. ROBUFFO GIORDANO, A. DE LUCA. *Dynamic Identification of the Franka Emika Panda Robot With Retrieval of Feasible Parameters Using Penalty-Based Optimization*, in "IEEE Robotics and Automation Letters", October 2019, vol. 4, n^o 4, pp. 4147-4154, (also presented at ICRA'19) [*DOI :* 10.1109/LRA.2019.2931248], https://hal.inria.fr/hal-02265293

[19] T. HOWARD, M. MARCHAL, A. LÉCUYER, C. PACCHIEROTTI. *PUMAH : Pan-tilt Ultrasound Mid-Air Haptics for larger interaction workspace in virtual reality*, in "IEEE Transactions on Haptics (ToH)", January 2020, pp. 1-6 [*DOI :* 10.1109/TOH.2019.2963028], https://hal.inria.fr/hal-02424247

[20] I.-F. KENMOGNE, V. DREVELLE, E. MARCHAND. *Cooperative Localization of Drones by using Interval Methods*, in "Acta Cybernetica", 2019, pp. 1-16, https://hal.inria.fr/hal-02339451

[21] A. KHEDDAR, S. CARON, P. GERGONDET, A. COMPORT, A. TANGUY, C. OTT, B. HENZE, G. MESESAN, J. ENGLSBERGER, M. A. ROA, P.-B. WIEBER, F. CHAUMETTE, F. SPINDLER, G. ORIOLO, L. LANARI, A. ESCANDE, K. CHAPPELLET, F. KANEHIRO, P. RABATE. *Humanoid robots in aircraft manufacturing*, in "IEEE Robotics and Automation Magazine", December 2019, vol. 26, n^o 4, pp. 30-45 [*DOI :* 10.1109/MRA.2019.2943395], https://hal-lirmm.ccsd.cnrs.fr/lirmm-02303117

[22] A. LÓPEZ, F. CHAUMETTE, E. MARCHAND, J. PETTRÉ. *Character navigation in dynamic environments based on optical flow*, in "Computer Graphics Forum", May 2019, vol. 38, n^o 2, pp. 181-192, Eurographics 2019 proceedings [*DOI :* 10.1111/CGF.13629], https://hal.inria.fr/hal-02052554

[23] E. MARCHAND. *Subspace-based Direct Visual Servoing*, in "IEEE Robotics and Automation Letters", July 2019, vol. 4, n^o 3, pp. 2699-2706, (also presented at IROS'19) [*DOI :* 10.1109/LRA.2019.2916263], https://hal.inria.fr/hal-02123993

[24] E. MARCHAND. *Direct visual servoing in the frequency domain*, in "IEEE Robotics and Automation Letters", April 2020, vol. 5, n^o 2, pp. 620-627 [*DOI :* 10.1109/LRA.2020.2965027], https://hal.inria.fr/hal-02290424

[25] B. PENIN, P. ROBUFFO GIORDANO, F. CHAUMETTE. *Minimum-Time Trajectory Planning Under Intermittent Measurements*, in "IEEE Robotics and Automation Letters", January 2019, vol. 4, n^o 1, pp. 153-160, (also presented at ICRA'19) [*DOI :* 10.1109/LRA.2018.2883375], https://hal.inria.fr/hal-01935466

[26] D. PRATTICHIZZO, M. OTADUY, H. KAJIMOTO, C. PACCHIEROTTI. *Wearable and Hand-Held Haptics*, in "IEEE Transactions on Haptics (ToH)", July 2019, vol. 12, n^o 3, pp. 227-231 [*DOI :* 10.1109/TOH.2019.2936736], https://hal.inria.fr/hal-02302243

[27] P. SALARIS, M. COGNETTI, R. SPICA, P. ROBUFFO GIORDANO. *Online Optimal Perception-Aware Trajectory Generation*, in "IEEE Transactions on Robotics", 2019, pp. 1-16 [*DOI :* 10.1109/TRO.2019.2931137], https://hal.inria.fr/hal-02278900

[28] S. VILLA SALAZAR, C. PACCHIEROTTI, X. DE TINGUY, A. MACIEL, M. MARCHAL. *Altering the Stiffness, Friction, and Shape Perception of Tangible Objects in Virtual Reality Using Wearable Haptics*, in "IEEE

Transactions on Haptics (ToH)", January 2020 [*DOI :* 10.1109/TOH.2020.2967389], https://hal.inria.fr/hal-02450301

[29] E. M. YOUNG, D. GUEORGUIEV, K. J. KUCHENBECKER, C. PACCHIEROTTI. *Compensating for Fingertip Size to Render Tactile Cues More Accurately*, in "IEEE Transactions on Haptics (ToH)", January 2020 [*DOI :* 10.1109/TOH.2020.2966993], https://hal.inria.fr/hal-02443460

[30] Z. ZAKE, F. CHAUMETTE, N. PEDEMONTE, S. CARO. *Vision-Based Control and Stability Analysis of a Cable-Driven Parallel Robot*, in "IEEE Robotics and Automation Letters", February 2019, vol. 4, n^{o} 2, pp. 1029-1036, (also presented ar ICRA'19) [*DOI :* 10.1109/LRA.2019.2893611], https://hal.archives-ouvertes.fr/hal-01987856

[31] Z. ZAKE, F. CHAUMETTE, N. PEDEMONTE, S. CARO. *Robust 2 1/2D Visual Servoing of a Cable-Driven Parallel Robot Thanks to Trajectory Tracking*, in "IEEE Robotics and Automation Letters", January 2020, vol. 5, n^{o} 2, pp. 660-667, https://arxiv.org/abs/2001.06324 [*DOI :* 10.1109/LRA.2020.2965033], https://hal.archives-ouvertes.fr/hal-02429717

[32] K. ZHANG, F. CHAUMETTE, J. CHEN. *Trifocal tensor-based 6-DOF visual servoing*, in "The International Journal of Robotics Research", September 2019, vol. 38, n^{o} 10-11, pp. 1208-1228 [*DOI :* 10.1177/0278364919872544], https://hal.inria.fr/hal-02276270

Invited Conferences

[33] F. CHAUMETTE. *Geometric and end-to-end robot vision-based control*, in "RoMoCo 2019 - 12th Int. Workshop on Robot Motion and Control (Plenary talk)", Poznan, Poland, July 2019, https://hal.inria.fr/hal-02406552

International Conferences with Proceedings

[34] J. AMIRIAN, J.-B. HAYET, J. PETTRÉ. *Social Ways: Learning Multi-Modal Distributions of Pedestrian Trajectories with GANs*, in "CVPR 2019 - IEEE Conference on Computer Vision and Pattern Recognition", Long Beach, United States, IEEE, June 2019, pp. 1-9, https://hal.inria.fr/hal-02108756

[35] J. AMIRIAN, W. VAN TOLL, J.-B. HAYET, J. PETTRÉ. *Data-Driven Crowd Simulation with Generative Adversarial Networks*, in "CASA '19 - International Conference on Computer Animation and Social Agents", Paris, France, March 2019, pp. 1-4 [*DOI :* 10.1145/3328756.3328769], https://hal.inria.fr/hal-02134282

[36] F. BERTON, A.-H. OLIVIER, J. BRUNEAU, L. HOYET, J. PETTRÉ. *Studying Gaze Behaviour During Collision Avoidance With a Virtual Walker: Influence of the Virtual Reality Setup*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, March 2019, pp. 717-725 [*DOI :* 10.1109/VR.2019.8798204], https://hal.inria.fr/hal-02058360

[37] J. BIMBO, C. PACCHIEROTTI, N. G. TSAGARAKIS, D. PRATTICHIZZO. *Collision detection and isolation on a robot using joint torque sensing*, in "IROS 2019 - IEEE/RSJ International Conference on Intelligent Robots and Systems", Macau, Macau SAR China, IEEE, November 2019, pp. 1-6, https://hal.inria.fr/hal-02197009

[38] J. CHEVRIE, A. KRUPA, M. BABEL. *Real-time Teleoperation of Flexible Beveled-tip Needle Insertion using Haptic Force Feedback and 3D Ultrasound Guidance*, in "ICRA 2019 - IEEE International Conference on Robotics and Automation", Montreal, Canada, IEEE, May 2019, pp. 1-7, https://hal.inria.fr/hal-02053101

[39] J. G. DA SILVA FILHO, A.-H. OLIVIER, A. CRÉTUAL, J. PETTRÉ, T. FRAICHARD. *Effective Human-Robot Collaboration in near symmetry collision scenarios*, in "RO-MAN 2019 - 28th IEEE International Conference on Robot & Human Interactive Communication", New Dehli, India, IEEE, October 2019, pp. 1-8, https://hal.inria.fr/hal-02267705

[40] X. DE TINGUY, C. PACCHIEROTTI, M. EMILY, M. CHEVALIER, A. GUIGNARDAT, M. GUILLAUDEUX, C. SIX, A. LÉCUYER, M. MARCHAL. *How different tangible and virtual objects can be while still feeling the same?*, in "WHC 2019 - IEEE World Haptics Conference", Tokyo, Japan, IEEE, July 2019, pp. 1-6 [*DOI :* 10.1109/WHC.2019.8816164], https://hal.inria.fr/hal-02121839

[41] X. DE TINGUY, C. PACCHIEROTTI, M. MARCHAL, A. LÉCUYER. *Toward Universal Tangible Objects: Optimizing Haptic Pinching Sensations in 3D Interaction*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, 2019, pp. 321-330 [*DOI :* 10.1109/VR.2019.8798205], https://hal.inria.fr/hal-02021319

[42] L. DEVIGNE, F. PASTEAU, T. CARLSON, M. BABEL. *A shared control solution for safe assisted power wheelchair navigation in an environment consisting of negative obstacles: a proof of concept*, in "SMC 2019 - IEEE International Conference on Systems, Man, and Cybernetics", Bari, Italy, IEEE, October 2019, pp. 1043-1048 [*DOI :* 10.1109/SMC.2019.8914211], https://hal.inria.fr/hal-02263532

[43] H. GURNEL, M. MARCHAL, L. LAUNAY, L. BEUZIT, A. KRUPA. *Design of haptic guides for pre-positioning assistance of a comanipulated needle*, in "SMC 2019 - IEEE International Conference on Systems, Man, and Cybernetics", Bari, Italy, IEEE, October 2019, pp. 478-485 [*DOI :* 10.1109/SMC.2019.8914395], https://hal.inria.fr/hal-02387192

[44] H. GURNEL, M. MARCHAL, L. LAUNAY, L. BEUZIT, A. KRUPA. *Preliminary evaluation of haptic guidance for pre-positioning a comanipulated needle*, in "SURGETICA 2019", Rennes, France, June 2019, pp. 1-3, https://hal.inria.fr/hal-02387214

[45] T. HOWARD, G. GALLAGHER, A. LÉCUYER, C. PACCHIEROTTI, M. MARCHAL. *Investigating the recognition of local shapes using mid-air ultrasound haptics*, in "WHC 2019 - IEEE World Haptics Conference", Tokyo, Japan, IEEE, July 2019, pp. 1-6 [*DOI :* 10.1109/WHC.2019.8816127], https://hal.inria.fr/hal-02121329

[46] A. LÓPEZ, F. CHAUMETTE, E. MARCHAND, J. PETTRÉ. *Attracted by light: vision-based steering virtual characters among dark and light obstacles*, in "MIG 2019 - ACM SIGGRAPH Conference Motion Interaction and Games", Newcastle upon Tyne, United Kingdom, ACM, October 2019, pp. 1-6 [*DOI :* 10.1145/3359566.3360085], https://hal.inria.fr/hal-02299397

[47] E. MARCHAND, F. CHAUMETTE, T. CHABOT, K. KANANI, A. POLLINI. *RemoveDebris Vision-Based Navigation preliminary results*, in "IAC 2019 - 70th International Astronautical Congress", Washington D.C., United States, October 2019, pp. 1-10, https://hal.inria.fr/hal-02315122

[48] B. NIAY, A.-H. OLIVIER, J. PETTRÉ, L. HOYET. *The Influence of Step Length to Step Frequency Ratio on the Perception of Virtual Walking Motions*, in "MIG 2019 - 12th annual ACM SIGGRAPH conference on Motion, Interaction and Games", Newcastle upon Tyne, United Kingdom, ACM Press, October 2019, pp. 1-2 [*DOI :* 10.1145/3359566.3364687], https://hal.archives-ouvertes.fr/hal-02378300

[49] A.-H. OLIVIER, N. LE BORGNE, M. BABEL, A. CRÉTUAL, J. PETTRÉ. *Evitement de collision entre un piéton et une personne sur un fauteuil roulant motorisé*, in "SOFPEL 2019 - 26ème congrès de la Société Francophone Posture, Équilibre et Locomotion", Montréal, Canada, December 2019, https://hal.inria.fr/hal-02373525

[50] R. RAHAL, F. ABI-FARRAJ, P. R. GIORDANO, C. PACCHIEROTTI. *Haptic Shared-Control Methods for Robotic Cutting under Nonholonomic Constraints*, in "IROS 2019 - IEEE/RSJ International Conference on Intelligent Robots and Systems", Macau, Macau SAR China, IEEE, November 2019, pp. 1-7, https://hal.inria.fr/hal-02197603

[51] M. SELVAGGIO, P. ROBUFFO GIORDANO, F. FICUCIELLO, B. SICILIANO. *Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance*, in "ICRA 2019 - IEEE International Conference on Robotics and Automation", Montreal, Canada, IEEE, May 2019, pp. 1-7, https://hal.inria.fr/hal-02051476

[52] A. SENGUPTA, A. KRUPA, E. MARCHAND. *RGB-D tracking of complex shapes using coarse object models*, in "ICIP 2019 - IEEE International Conference on Image Processing", Taipei, Taiwan, IEEE, September 2019, pp. 1-5 [*DOI :* 10.1109/ICIP.2019.8803574], https://hal.inria.fr/hal-02129243

[53] A. SENGUPTA, A. KRUPA, E. MARCHAND. *Tracking of Non-Rigid Objects using RGB-D Camera*, in "SMC 2019 - IEEE International Conference on Systems, Man, and Cybernetics", Bari, Italy, IEEE, October 2019, pp. 3310-3317 [*DOI :* 10.1109/SMC.2019.8914543], https://hal.inria.fr/hal-02178353

[54] G. VAILLAND, F. GRZESKOWIAK, L. DEVIGNE, Y. GAFFARY, B. FRAUDET, E. LEBLONG, F. NOUVIALE, F. PASTEAU, R. LE BRETON, S. GUEGAN, V. GOURANTON, B. ARNALDI, M. BABEL. *User-centered design of a multisensory power wheelchair simulator: towards training and rehabilitation applications*, in "ICORR 2019 - International Conference on Rehabilitation Robotics", Toronto, Canada, 2019, pp. 1-6, https://hal.inria.fr/hal-02134530

[55] W. VAN TOLL, J. PETTRÉ. *Connecting Global and Local Agent Navigation via Topology*, in "MIG 2019 - ACM SIGGRAPH Conference Motion Interaction and Games", Newcastle upon Tyne, United Kingdom, ACM, October 2019, pp. 1-10 [*DOI :* 10.1145/3359566.3360084], https://hal.inria.fr/hal-02308297

[56] Z. ZAKE, S. CARO, A. SUAREZ ROOS, F. CHAUMETTE, N. PEDEMONTE. *Stability Analysis of Pose-Based Visual Servoing Control of Cable-Driven Parallel Robots*, in "CableCon 2019 - Fourth International Conference on Cable-Driven Parallel Robots", Krakow, Poland, June 2019, pp. 1-12 [*DOI :* 10.1007/978-3-030-20751-9_7], https://hal.archives-ouvertes.fr/hal-02127451

National Conferences with Proceedings

[57] T. DUVERNE, T. ROUGNANT, F. LE YONDRE, F. BERTON, J. BRUNEAU, L. HOYET, J. PETTRÉ, A.-H. OLIVIER. *Analyse des réactions corporelles à la transgression des normes de proxémie en contexte de spectacle sportif : expérimentations en situations réelles et virtuelles*, in "ACAPS 2019 - 18ème congrès de l'Association des Chercheurs en Activités Physiques et Sportives", Paris, France, October 2019, https://hal.inria.fr/hal-02393360

Conferences without Proceedings

[58] L. DEVIGNE, M. BABEL, R. LE BRETON, E. LEBLONG, V. GOURANTON, F. PASTEAU, B. FRAUDET, S. GUEGAN, G. VAILLAND, Y. GAFFARY. *Expérience de conduite en fauteuil roulant dans une ville virtuelle avec un simulateur multisensoriel conçu selon une approche centrée sur l'utilisateur : une étude de cas*, in

"SOFMER 2019 - 34ème congrès de la Société Français de Médecine Physique et de Réadaptation", Bordeaux, France, October 2019, https://hal.inria.fr/hal-02339573

[59] P. GALIEN, S. ACHILLE-FAUVEAU, E. LEBLONG, A. DURUFLE, M. BABEL, B. FRAUDET, N. BENOIT. *Vision croisée sur la robotique d'assistance dans la vie quotidienne des patients et des aidants*, in "SOFMER 2019 - 34ème congrès de la Société Français de Médecine Physique et de Réadaptation", Bordeaux, France, October 2019, https://hal.inria.fr/hal-02339550

[60] S. LYNCH, R. KULPA, L. A. MEERHOFF, A. SOREL, J. PETTRÉ, A.-H. OLIVIER. *Collision avoidance between walkers with a twist: strategies for curvilinear and rectilinear paths*, in "ISPGR 2019 - Conference of the International Society for Posture & Gait Research", Edinburgh, United Kingdom, June 2019, https://hal.inria.fr/hal-02058340

[61] B. NIAY, A.-H. OLIVIER, J. PETTRÉ, L. HOYET. *The Influence of Step Length to Step Frequency Ratio on the Perception of Virtual Walking Motions*, in "ACM SIGGRAPH Symposium on Applied Perception", Barcelone, Spain, September 2019, https://hal.archives-ouvertes.fr/hal-02395303

[62] A.-H. OLIVIER, N. LE BORGNE, M. BABEL, A. CRÉTUAL, J. PETTRÉ. *Collision avoidance between a walker and a person on an electric powered wheelchair*, in "ISPGR 2019 - Conference of the International Society for Posture & Gait Research", Edinburgh, United Kingdom, June 2019, https://hal.inria.fr/hal-02058342

Scientific Books (or Scientific Book chapters)

[63] F. CHAUMETTE. *Robot Visual Control*, in "Encyclopedia of Systems and Control, 2nd edition", J. BAILLIEUL, T. SAMAD (editors), Springer London, December 2020, pp. 1-18 [*DOI :* 10.1007/978-1-4471-5102-9_170-2], https://hal.inria.fr/hal-02422019

[64] E. MARCHAND. *Visual Tracking*, in "Encyclopedia of Robotics", Springer, 2020, pp. 1-16, forthcoming, https://hal.inria.fr/hal-02426694

[65] A. SPADA, M. COGNETTI, A. DE LUCA. *Locomotion and Telepresence in Virtual and Real Worlds*, in "Locomotion and Telepresence in Virtual and Real Worlds", S. P. IN ADVANCED ROBOTICS (editor), June 2019, pp. 85-98 [*DOI :* 10.1007/978-3-319-89327-3_7], https://hal.inria.fr/hal-02265284

Other Publications

[66] C. GAZ, M. COGNETTI, A. OLIVA, P. ROBUFFO GIORDANO, A. DE LUCA. *Dynamic Identification of the Franka Emika Panda Robot with Retrieval of Feasible Parameters Using Penalty-Based Optimization*, October 2019, pp. 1-9, Supplementary material, https://hal.inria.fr/hal-02265294