RESEARCH CENTRE
**Inria Center
at Rennes University**

IN PARTNERSHIP WITH:

CNRS, Université Rennes 1, Institut national des sciences appliquées de Rennes

2022
ACTIVITY REPORT

Project-Team

RAINBOW

Sensor-based Robotics and Human Interaction

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

DOMAIN

Perception, Cognition and Interaction

THEME

Robotics and Smart environments

Innia

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Project-Team RAINBOW

Creation of the Project-Team: 2018 June 01

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2   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 of autonomously executing specific and repetitive tasks, with great speed and precision, and of 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, of taking 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 interested 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 → robot) and *backward* (robot → 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
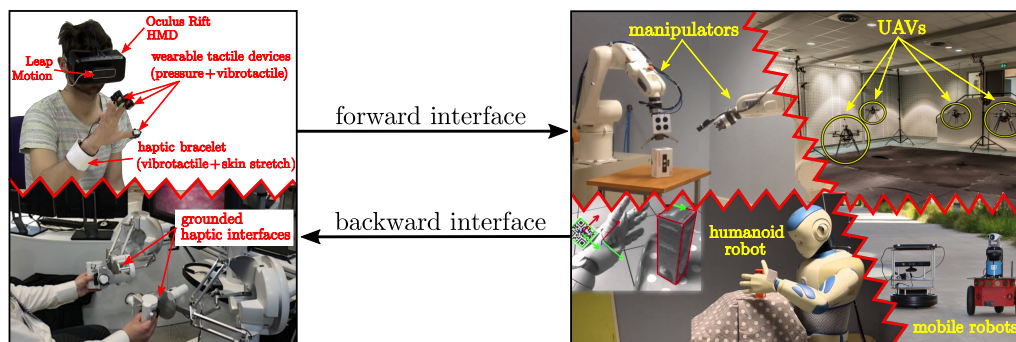
Figure 1: An illustration of the *prototypical* activities foreseen in Rainbow in which a human operator is in partial (and high-level) control of single/multiple complex robots performing semi-autonomous tasks

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 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 of 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 or for system design (choice of the best sensors 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 little need for data pre-processing which can minimize feature extraction errors and, in general, improve the overall robustness/accuracy (since all the available data is used by the motion controller); (*ii*) sensor-based interaction with objects of unknown/deformable shapes, for gaining the ability to manipulate, e.g., flexible objects from the acquired sensed data (e.g., controlling online a needle being inserted in a flexible tissue); (*iii*) sensor-based model predictive control, by developing *online/reactive* trajectory optimization methods able to plan feasible trajectories for robots subjects to sensing/actuation constraints with the possibility of (onboard) sensing for continuously replanning (over some future time horizon) the optimal trajectory. These methods will play an important role when dealing with complex robots affected by complex sensing/actuation constraints, for which pure reactive strategies (as in most of the previous Lagadic works) are not effective. Furthermore, the coupling with the aforementioned optimal sensing will also be considered; (*iv*) multi-robot decentralised estimation and control, with the aim of devising again sensor-based strategies for groups of multiple robots needing to maintain a formation or perform navigation/manipulation tasks. Here, the challenges come from the need of devising "simple" decentralized and scalable control strategies under the presence of complex sensing constraints (e.g., when using onboard cameras, limited fov, occlusions). Also, the need of locally estimating global quantities (e.g., common frame of reference, global property of the formation such as connectivity or rigidity) will also be a line of active research.

3.2.3   Haptics for Robotics Applications

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

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

3.2.4   Shared Control of Complex Robotics Systems

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

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

4 Application domains

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

- applications involving remote telemanipulation with one or two robot arms, where the arm(s) will need to coordinate their motion for approaching/grasping objects of interest under the guidance of a human operator;

- applications involving single and multiple mobile robots for spatial navigation tasks (e.g., exploration, surveillance, mapping). In the multi-robot case, the high redundancy of the multi-robot group will motivate research in autonomously exploiting this redundancy for facilitating the task (e.g., optimizing the self-localization of the environment mapping) while following the human commands, and vice-versa for informing the operator about the status of a multi-robot group. In the single robot case, the possible combination with some manipulation devices (e.g., arms on a wheeled robot) will motivate research into remote tele-navigation and tele-manipulation;

- applications involving medical robotics, in which the "manipulators" are replaced by the typical tools used in medical applications (ultrasound probes, needles, cutting scalpels, and so on) for semi-autonomous probing and intervention;

- applications involving a direct physical "coupling" between human users and robots (rather than a "remote" interfacing), such as the case of assistive devices used for easing the life of impaired people. Here, we will be primarily interested in, e.g., safety and usability issues, and also touch some aspects of user acceptability.

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

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

5 Highlights of the year

5.1 Awards

- C. Pacchierotti has received the CNRS Bronze Medal (institute INS2I)

- M. Marchal, M. Babel, and C. Pacchierotti have received the "Best Paper Award", Eurohaptics 2022, Hamburg, Germany

- C. Pacchierotti receives the "RAS Most Active Technical Committee Award" for the IEEE RAS Technical Committee on Haptics, during his tenure as Chair

- Maxime Robic has been awarded as the winner of the 3rd jury price of "Ma thèse en 180 secondes" during the national final in Lyon in May 2022.

5.2   Highlights

- P. Robuffo Giordano is one of the two IEEE RAS Distinguished Lecturers for Multi-Robot Systems

- Horizon Europe project RĔGO started in October 2022

6   New software and platforms

6.1   New software

6.1.1   HandiViz

Name: 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.

Contact: Marie Babel

Participants: François Pasteau, Marie Babel

Partner: INSA Rennes

6.1.2   UsTk

Name: 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.

URL: https://ustk.inria.fr

Contact: Alexandre Krupa

Participants: Alexandre Krupa, Fabien Spindler

Partners: Inria, Université de Rennes 1

6.1.3   ViSP

Name: 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.

We have extended ViSP with a new open-source dynamical simulator named FrankaSim based on CoppeliaSim and ROS for the popular Franka Emika Robot [2]. The simulator fully integrated in the ViSP ecosystem features a dynamic model that has been accurately identified from a real robot, leading to more realistic simulations. Conceived as a multipurpose research simulation platform, it is well suited for visual servoing applications as well as, in general, for any pedagogical purpose in robotics. All the software, models and CoppeliaSim scenes presented in this work are publicly available under free GPL-2.0 license.

[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. URL: https://hal.inria.fr/inria-00351899v1

[2] A. A. Oliva, F. Spindler, P. Robuffo Giordano and F. Chaumette. 'FrankaSim: A Dynamic Simulator for the Franka Emika Robot with Visual-Servoing Enabled Capabilities'. In: ICARCV 2022 - 17th International Conference on Control, Automation, Robotics and Vision. Singapore, Singapore, 11th Dec. 2022, pp. 1–7. URL: https://hal.inria.fr/hal-03794415.

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.

URL: `https://visp.inria.fr`

Contact: Fabien Spindler

Participants: Éric Marchand, Fabien Spindler, François Chaumette

Partners: Inria, Université de Rennes 1

6.1.4   DIARBENN

Name: Obstacle avoidance through sensor-based servoing

Keywords: Servoing, Shared control, Navigation

Functional Description: DIARBENN's objective is to define an obstacle avoidance solution adapted to a mobile robot such as a powered wheelchair. Through a shared control system, the system corrects progressively and if necessary the trajectory when approaching an obstacle while respecting the user's intention.

Contact: Marie Babel

Participants: Marie Babel, François Pasteau, Sylvain Guegan

Partner: INSA Rennes

6.2 New platforms

The platforms described in the next sections are labeled by the University of Rennes 1 and by ROBOTEX 2.0.

6.2.1 Robot Vision Platform

Participant: François Chaumette, 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). The Gantry robot allows mounting grippers on its end-effector. Attached to these robots, we can also find a collection of various RGB and RGB-D cameras used to validate vision-based real-time tracking algorithms.

In 2022, this platform has been used to validate experimental results in 3 accepted publications [15, 42, 41].
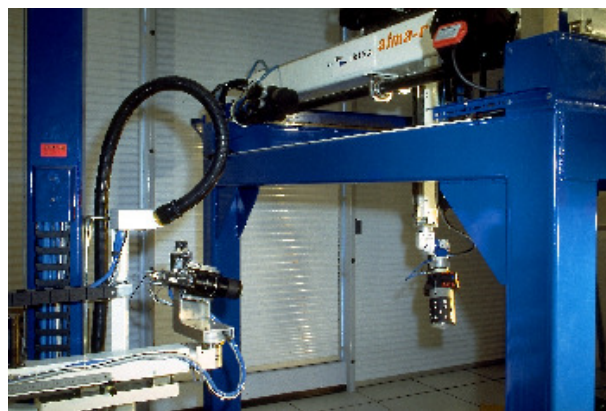
Figure 2: Rainbow robotics platform for vision-based manipulation

6.2.2 Mobile Robots

Participants: Marie Babel, François Pasteau, Fabien Spindler *(contact)*.

To validate our research in personally assisted living topic (see Sect. 7.4.3), we have three electric wheelchairs, one from Permobil, one from Sunrise and the last from YouQ (see Fig. 3.a). 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. A wheelchair haptic simulator completes this platform to develop new human interaction strategies in a virtual reality environment (see Fig. 3(b)).

Pepper, a human-shaped robot designed by SoftBank Robotics to be a genuine day-to-day companion (see Fig. 3.c) 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 and visual exploration strategies (Sect. 7.2.6).

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

In 2022, these platforms were used to obtain experimental results presented in 3 papers [21, 36, 28].

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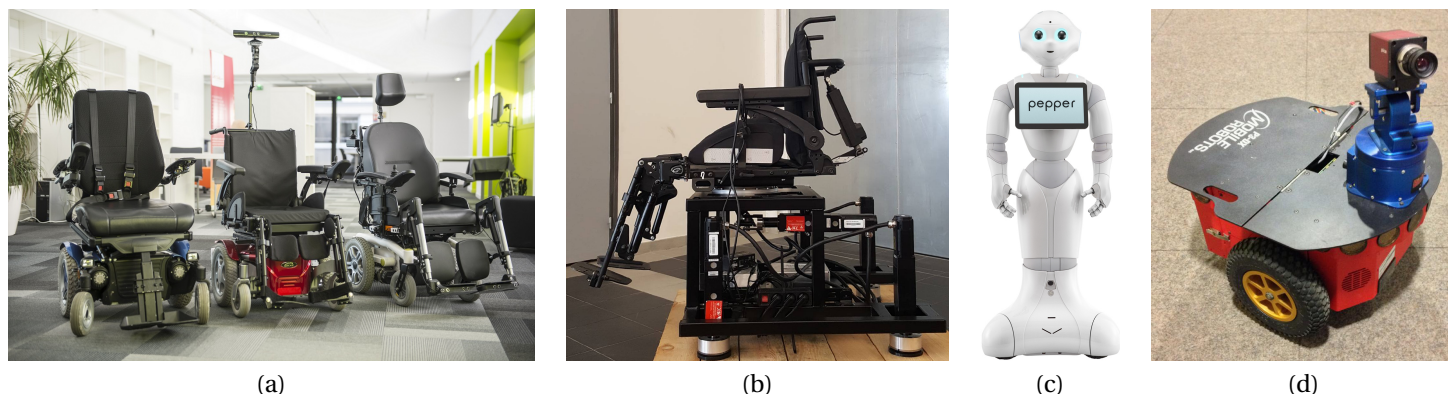
Figure 3: Mobile Robot Platform. a) wheelchairs from Permobil, Sunrise and YouQ, b) Wheelchair haptic simulator, c) Pepper human-shaped robot, d) Pioneer P3-DX robot

6.2.3 Advanced Manipulation Platform

Participants: Alexandre Krupa, Claudio Pacchierotti, Paolo Robuffo Giordano, François Chaumette, Fabien Spindler *(contact)*.

This platform is composed by 2 Panda lightweight arms from Franka Emika equipped with torque sensors in all seven axes. An electric gripper, a camera, a soft hand from qbrobotics or a Reflex TakkTile 2 gripper from RightHand Labs (see Fig. 4.b) can be mounted on the robot end-effector (see Fig. 4.a). A force/torque sensor from Alberobotics is also attached to one of the robots end-effector to get more precision during torque control. This setup is used to validate our activities in coupling force and vision for controlling robot manipulators (see Section 7.2.11) and in controlling the deformation of soft objects (Sect. 7.2.7). Other haptic devices (see Section 6.2.5) can also be coupled to this platform.

This year we stopped the medical robotics platform and integrated the two 6 DoF Adept Viper arms that were part of it into this advanced manipulation platform. The two Vipers are now used to manipulate deformable objects. We also introduce a new UR 5 robot that was primary used in the Hybrid team.

5 new papers [35, 39, 43, 38, 26] and 1 PhD thesis [51] published this year include experimental results obtained with this platform.

6.2.4 Unmanned Aerial Vehicles (UAVs)

Participants: Joudy Nader, Paolo Robuffo Giordano, Claudio Pacchierotti, Pierre Perraud, Fabien Spindler *(contact)*.

(a)   (b)   (c)

Figure 4: 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, c) The 5 arms composing the platform with in the foreground a Franka, in the second plan our two Viper robots, then in the background, a UR 5 arm and our second Franka robot.

Rainbow is involved in several activities involving perception and control for single and multiple quadrotor UAVs. To this end, we exploit four qu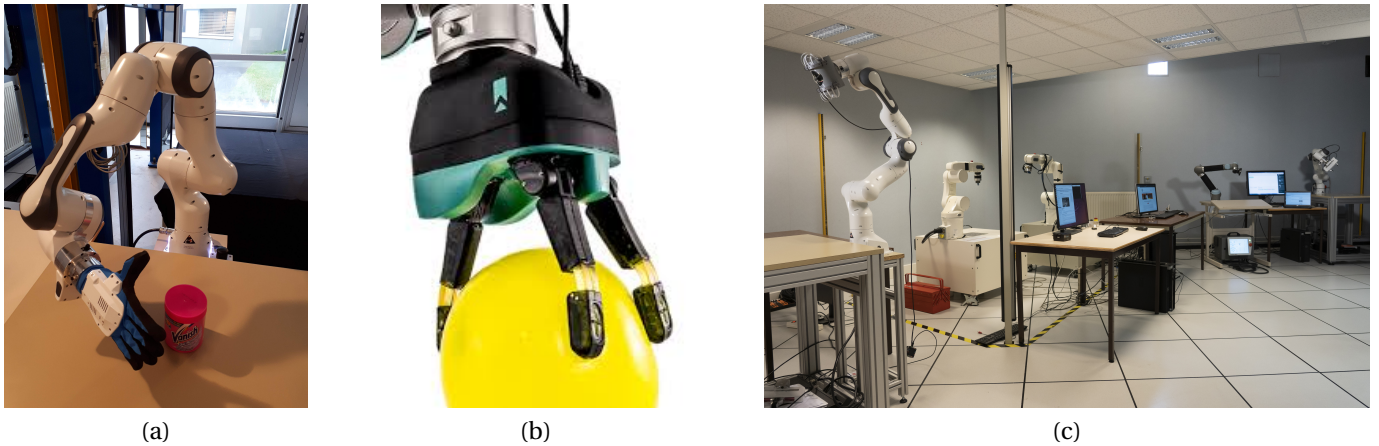adrotors from Mikrokopter Gmbh, Germany (see Fig. 5.a), and one quadrotor from 3DRobotics, USA (see Fig. 5.b). The Mikrokopter quadrotors have been heavily customized by: (i) reprogramming from scratch the low-level attitude controller onboard the micro-controller of the quadrotors, (ii) equipping each 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 new Realsense RGB-D cameras for visual odometry and visual servoing. 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 we equipped a meeting room with a Qualisys motion capture system. This room is used as a second flying arena from January to August and allows us to fly our drones in a much larger volume than the first arena.

To make evolve the platform's hardware, we began testing a new drone architecture based on a DJI F450 equipped with a Pixhawk, a Jetson TX2 and an Intel Realsense D405 RGB-D camera. The first experiments allowed us to carry out a visual servoing using ViSP to position the drone w.r.t. a target.

This year, 1 paper [10] contains experimental results obtained with this platform.

(a)   (b)   (c)
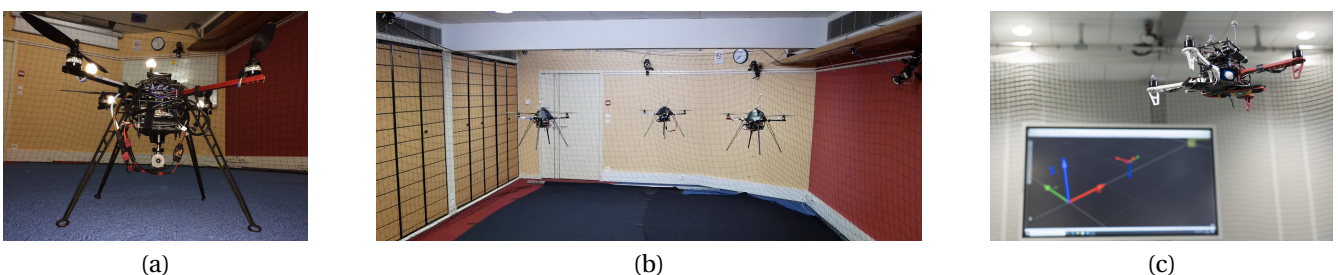
Figure 5: Unmanned Aerial Vehicles Platform. a) Quadrotor XL1 from Mikrokopter, b) Formation control with 3 XL1 from Mikrokopter in our flying arena equipped with the Vicon localization system, (c) DJI F540 equipped with a Pixhawk and a Jetson TX2 flying in our new arena equipped with a Qualisys Motion Capture system.

6.2.5 Haptics and Shared Control Platform

Participants: Claudio Pacchierotti, Paolo Robuffo Giordano, Maud Marchal, Marie Babel, Fabien Spindler *(contact)*.

Various haptic devices are used to validate our research in shared control. We design wearable haptics devices to give user feedback and use also some devices out of the shelf. We have a Virtuose 6D device from Haption (see Fig. 6.a). This device is used as master device in many of our shared control activities. It could also be coupled to the Haption haptic glove in loan from the University of Birmingham. An Omega 6 (see Fig. 6.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 7 papers [10, 13, 30, 31, 32, 26, 17] and 1 HdR [52] published this year.

(a) (b) (c)
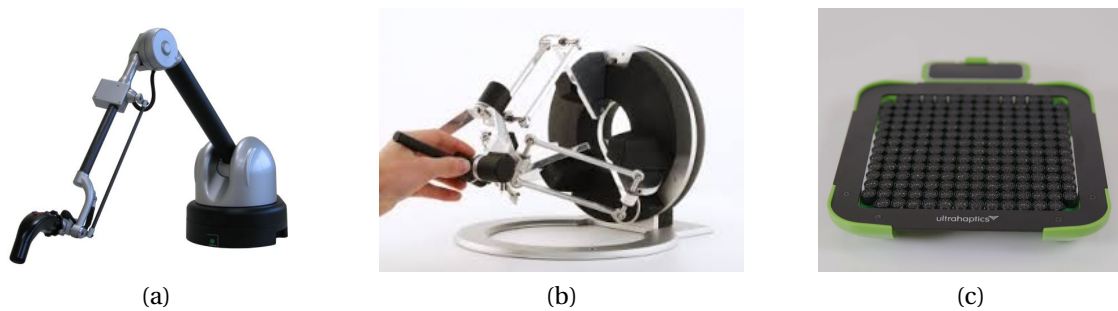
Figure 6: Haptics and Shared Control Platform. a) Virtuose 6D, b) Omega 6 haptic devices, c) Ultraleap STRATOS.

6.2.6 Portable immersive room

Participants: François Pasteau, Fabien Grzeskowiak, Marie Babel *(contact)*.

To validate our research on assistive robotics and its applications in virtual conditions, we very recently acquire a portable immersive room that is planned to be easily deployed in different rehabilitation structures in order to conduct clinical trials. The system has been designed by Trinoma company and has been funded by Interreg ADAPT project.

As the platform is very new, there has been no related publication this year.

(a) (b)
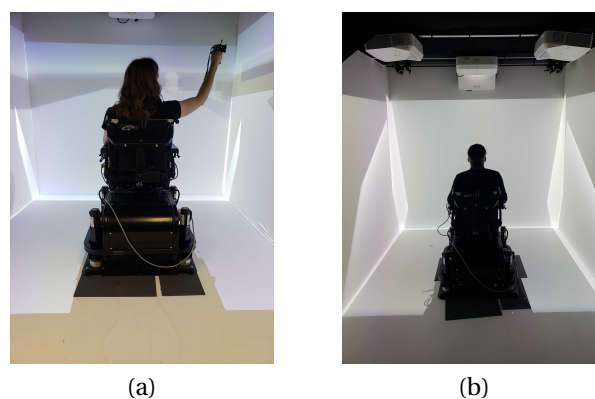
Figure 7: Portable Immersive Room and the multisensory wheelchair driving simulator

7 New results

7.1 Optimal and Uncertainty-Aware Sensing

7.1.1 Trajectory Generation for Optimal State Estimation

Participants: Nicola De Carli, Claudio Pacchierotti, 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 (few) noisy outputs (i.e., sensor readings) while at the same time reducing the negative effects of the process/actuation noise. We have previously 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) [55].

In [37] we have considered an active sensing problem that involves multiple robots in an *environmental monitoring* task over long time horizons. The approach exploits the norm of the constructability Gramian for learning a distributed multi-robot control policy using the reinforcement learning paradigm. The learned policy is then combined with energy constraints using the constraint-driven control framework in order to achieve persistent environmental monitoring. The proposed approach is tested in a simulated multi-robot persistent environmental monitoring scenario where a team of robots with limited availability of energy is to be controlled in a coordinated fashion in order to estimate the concentration of a gas diffusing in the environment.

7.1.2 Leveraging Multiple Environments for Learning and Decision Making

Participants: Maud Marchal, Thierry Gaugry, Antonin Bernardin.

Learning is usually performed by observing real robot executions. Physics-based simulators are a good alternative for providing highly valuable information while avoiding costly and potentially destructive robot executions. Within the Imagine project, we presented a novel approach for learning the probabilities of symbolic robot action outcomes. This is done by leveraging different environments, such as physics-based simulators, in execution time. To this end, we proposed MENID (Multiple Environment Noise Indeterministic Deictic) rules, a novel representation able to cope with the inherent uncertainties present in robotic tasks. MENID rules explicitly represent each possible outcomes of an action, keep memory of the source of the experience, and maintain the probability of success of each outcome. We also introduced an algorithm to distribute actions among environments, based on previous experiences and expected gain. Before using physics-based simulations, we proposed a methodology for evaluating different simulation settings and determining the least time-consuming model that could be used while still producing coherent results. We demonstrated the validity of the approach in a dismantling use case, using a simulation with reduced quality as simulated system, and a simulation with full resolution where we add noise to the trajectories and some physical parameters as a representation of the real system.

7.1.3 Visual SLAM

Participant: Mathieu Gonzalez, Eric Marchand.

We propose a new SLAM system that uses the semantic segmentation of objects and structures in the scene. Semantic information is relevant as it contains high level information which may make SLAM more accurate and robust. Our contribution is twofold: i) A new SLAM system based on ORB-SLAM2 that creates a semantic map made of clusters of points corresponding to objects instances and structures in

the scene. ii) A modification of the classical Bundle Adjustment formulation to constrain each cluster using geometrical priors, which improves both camera localization and reconstruction and enables a better understanding of the scene. This work [27][46] was done in cooperation with the IRT B-Com.

We extend this approach to dynamic environment. Indeed, classical visual simultaneous localization and mapping algorithms usually assume the environment to be rigid. This assumption limits the applicability of those algorithms as they are unable to accurately estimate the camera poses and world structure in real life scenes containing moving objects (e.g. cars, bikes, pedestrians, etc.). To tackle this issue, we propose TwistSLAM: a semantic, dynamic and stereo SLAM system that can track dynamic objects in the environment. Our algorithm creates clusters of points according to their semantic class. Thanks to the definition of inter-cluster constraints modeled by mechanical joints (function of the semantic class), a novel constrained bundle adjustment is then able to jointly estimate both poses and velocities of moving objects along with the classical world structure and camera trajectory. This work [16] was done in cooperation with the IRT B-Com.

We also proposed a novel binary graph descriptor to improve loop detection for visual SLAM systems. Our contribution is twofold: i) a graph embedding technique for generating binary descriptors which conserve both spatial and histogram information extracted from images; ii) a generic mean of combining multiple layers of heterogeneous data into the proposed binary graph descriptor, coupled with a matching and geometric checking method. We also introduce an implementation of our descriptor into an incremental Bag-of-Words (iBoW) structure that improves efficiency and scalability, and propose a method to interpret Deep Neural Network (DNN) results. This work [22] was done in cooperation with the Mimetic team.

7.2 Advanced Sensor-Based Control

7.2.1 Trajectory Generation for Minimum Closed-Loop State Sensitivity

Participants: Pascal Brault, Ali Srour, Simon Wasiela, 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. This activity in the scope of the ANR project CAMP (Sect. 9.3).

Over the past years, we have developed the notion of closed-loop "state sensitivity" and "input sensitivity" metrics. These allow formulating an optimal trajectory optimization problem whose solution results in a reference trajectory that, when perturbed, requires minimal change of the control inputs and has minimal deviations in the final tracking error. In [23] we have shown how one can formulate an optimization problem for generating a trajectory that minimizes the sensitivity to uncertain parameters and, at the same time, maximizes the observability of states to be estimated. These two objectives are shown to be competing against each other in the general case, and a suitable pareto-based strategy is introduced for optimizing the two objectives at once. During the year we have also worked on several additional extensions that resulted in three papers submitted to the next ICRA 2023 conference.

- together with Ali Srour we have extended the trajectory optimization problem to also consider the control gains as possible optimization variables. We could then generate minimally-sensitive trajectories that further reduce the state sensitivity by a proper choice of the control gains. The idea has been tested on three case studies involving a 3D quadrotor with a Lee (geometric) controller, a near-hovering (NH) controller and a sliding mode controller. The results of a large-scale simulative campaign showed an interesting pattern in the approach to the final hovering state, as well as unexpected trends in the optimized gains (e.g., from a statistical point of view, the "derivative" gains of the position loop were often reduced w.r.t. their initial values whereas the proportional gains were increased in average). These findings motivate us to keep working on the idea of jointly optimizing the motion and control gains for attaining robustness

- together with Pascal Brault, we have developed a novel algorithm for computing the tubes of perturbed state trajectories given a known range for the parametric uncertainty. The computation of the tubes can be easily obtained from the knowledge of the state sensitivity matrix, and the tube computation can be extended to any function of the states (including the control action). Availability of the tubes allows then formulating an improved trajectory optimization problem in which the size of the tube is minimized (rather than a generic norm of the state sensitivity matrix), and the tubes on the inputs (or any other function of the states) can be used in the constraints for enforcing a "robust" constraint satisfaction

- together with Simon Wasiela (LAAS-CNRS), we have proposed a global control-aware motion planner for optimizing the state sensitivity metric and producing collision-free reference motions that are robust against parametric uncertainties for a large class of complex dynamical systems. In particular, we have proposed a RRT*-based planner called SAMP that uses an appropriate steering method to first compute a (near) time-optimal and kinodynamically feasible trajectory that is then locally deformed to improve robustness and decrease its sensitivity to uncertainties. The evaluation performed on planar/full-3D quadrotor UAV models shows that the SAMP method produces low sensitivity robust solutions with a much higher performance than a planner directly optimizing the sensitivity.

7.2.2 UWB beacon navigation of assisted power wheelchair

Participants: Vincent Drevelle, Marie Babel, Eric Marchand, François Pasteau.

New sensors, based on ultra-wideband (UWB) radio technology, are emerging for indoor localization and object tracking applications. Contrarily to vision, these sensors are low-cost, non-intrusive and easy to adapt on the wheelchair. They enable measuring distances between fixed beacons and mobile sensors. We seek to exploit these UWB sensors for the navigation of a wheelchair, despite the low accuracy of the measurements they provide. The problem here lies in defining an autonomous or shared sensor-based control solution, which takes into account the measurement uncertainty related to UWB beacons.

Because of multipath or non-line-of-sight propagation, erroneous measurements can perturb radio beacon ranging in cluttered indoors environment. This happens when people, objects or even the wheelchair and its driver mask the direct line-of-sight between the two beacons.

We designed a robust wheelchair positioning method, based on an extended Kalman filter with outlier identification and rejection. The method fuses UWB range measurements with low-cost gyro and motor commands to estimate the orientation and position of the wheelchair. A dataset with various density of people around the wheelchair driver has been recorded. Preliminary results show decimeter-level planar accuracy in crowded environment.

Based on this pose estimator, a demonstration of autonomous navigation between defined poses has been shown to practitioners and power wheelchair users during the IH2A boot camp. This will provide the ground of coarse-grained navigation, while the use of sensor-based control and complementary sensors is investigated for precision tasks.

7.2.3 Singularity and stability issues in visual servoing

Participant: François Chaumette.

This study is done in the scope of the ANR Sesame project (see Section 9.3). Following our previous works about the complete determination of the singular configurations of image-based visual servoing using four points, we are now interested in determining the complete set of local minima and saddle points when using again point coordinates as visual features and classical controllers based on the pseudo-inverse of the interaction matrix or following a Levenberg-Marquardt minimization strategy.

Preliminary results based on a clever modeling of the system and the intensive use of symbolic calculation are promising.

7.2.4   Multi-sensor-based control for accurate and safe assembly

Participants: John Thomas, François Pasteau, François Chaumette.

This study is done in the scope of the BPI Lichie project 9.3. Its goal is to design sensor-based control strategies coupling vision and proximetry data for ensuring precise positioning while avoiding obstacles in dense environments. The targeted application is the assembly of satellite parts.

In a first part of this study, we designed a general ring of proximetry sensors and modeled the system so that tasks such that plane-to-plane positioning can be achieved [43].

7.2.5   Visual servo of a satellite constellation

Participants: Maxime Robic, Eric Marchand, François Chaumette.

This study is also done in the scope of the BPI Lichie project 9.3. Its goal is to control the orientation of a satellite constellation from a camera mounted on each of them to track particular objects on the ground. In a first part, we concentrated on a single satellite and designed an image-based control scheme able to compensate for the satellite, Earth, and potential object motions [42]. This control scheme has then be adapted in order to take into account the dynamic response of the satellite [41]

7.2.6   Visual Exploration of an Indoor Environment

Participants: Thibault Noël, Eric Marchand, François Chaumette.

This study is done in collaboration with the Creative company in Rennes (see Section 7.2.6). It is devoted to the exploration of indoor environments by a mobile robot, typically Pepper (see Section 6.2.2), for a complete and accurate reconstruction of the environment.

In this context, we studied a new sampling-based path planning approach, focusing on the challenges linked to autonomous exploration. The proposed method relies on the definition of a disk graph of free-space bubbles, from which we derive a biased sampling function that expands the graph towards known free space for maximal navigability and frontiers discovery. The proposed method demonstrates an exploratory behavior similar to Rapidly-exploring Random Trees, while retaining the connectivity and flexibility of a graph-based planner. We demonstrate the interest of our method by first comparing its path planning capabilities against state-of-the-art approaches, before discussing exploration-specific aspects, namely replanning capabilities and incremental construction of the graph. A simple frontiers-driven exploration controller derived from the proposed planning method has also been demonstrated [36]

7.2.7   Model-Based Deformation Servoing of Soft Objects

Participants: Fouad   Makiyeh,   Alexandre   Krupa,   Maud   Marchal, François Chaumette.

This study takes place in the context of the GentleMAN project (see Section 9.1.2). We proposed a complete pipeline for positioning a feature point of a soft object to a desired 3D position, by acting on a different manipulation point using a robotic manipulator. For that purpose, the analytic relation between the feature point displacement and the robot motion was derived using a coarse mass-spring

model (MSM), while taking into consideration the propagation delay introduced by a MSM. From this modeling step, a novel closed-loop controller was designed for performing the positioning task. To get rid of the model approximations, the object is tracked in real-time using a RGB-D sensor, thus allowing to correct on-line any drift between the object and its model. Our model-based and vision-based controller was validated in real experiments and the results showed promising performance in terms of accuracy, efficiency and robustness [35].

7.2.8   Constraint-based simulation of passive suction cups

Participants: Maud Marchal.

In [12], we proposed a physics-based model of suction phenomenon to achieve simulation of deformable objects like suction cups. Our model uses a constraint-based formulation to simulate the variations of pressure inside suction cups. The respective internal pressures are represented as pressure constraints which are coupled with anti-interpenetration and friction constraints. Furthermore, our method is able to detect multiple air cavities using information from collision detection. We solve the pressure constraints based on the ideal gas law while considering several cavity states. We test our model with a number of scenarios reflecting a variety of uses, for instance, a spring loaded jumping toy, a manipulator performing a pick and place task, and an octopus tentacle grasping a soda can. We also evaluate the ability of our model to reproduce the physics of suction cups of varying shapes, lifting objects of different masses, and sliding on a slippery surface. The results show promise for various applications such as the simulation in soft robotics and computer animation.

7.2.9   Manipulation of a deformable wire by two UAVs

Participants: Lev Smolentsev, Alexande Krupa, François Chaumette.

This study takes place in the context of the CominLabs MAMBO project (see Section 9.4). Its main objective is the development of a visual-based control framework for performing autonomous manipulation of a deformable wire attached between two UAVs using data provided by onboard RGB-D cameras. Toward this direction, we developed a visual servoing approach that controls the deformation of a suspended tether cable subject to gravity. The cable shape is modelled with a parabolic curve together with the orientation of the plane containing the tether. The visual features considered are the parabolic coefficients and the yaw angle of that plane. We derived the analytical expression of the interaction matrix that relates the variation of these visual features to the velocities of the cable extremities. Simulations and experimental results obtained with a robotic arm manipulating one extremity of the cable with an eye-to-hand configuration demonstrated the efficiency of this visual servoing approach to deform the tether cable toward a desired shape configuration. This work has been submitted in September to the next IEEE ICRA conference.

7.2.10   Multi-Robot Formation Control and Localization

Participant: Paolo Robuffo Giordano, Claudio Pacchierotti, Maxime Bernard, Nicola De Carli, Lorenzo Balandi.

Systems composed by multiple robots are useful in several applications where complex tasks need to be performed. Examples range from target tracking, to search and rescue operations and to load transportation. In many cases, it is desirable to have a flexible formation where interaction links can be created/lost at runtime depending on the task and environment (e.g., for better maneuvering in cluttered spaces). In [14] we have considered the problem of identifying in a decentralized way a possibly faulty

robot in the group, and then proposed a decentralized procedure for reconfigure the group topology for safely removing the faulty agent. The approach is validated via numerical simulations.

Another important problem for multi-robot applications is the need of having a good inter-robot localization (i.e., estimation of relative poses) for then implementing any higher-level formation control. In this context, we have worked on a decentralized trajectory optimization problem that allows a group of robots to (reactively) replan individual optimal trajectories for estimating at best their relative poses from the available measurements (e.g., distances of bearings). This work in now in preparation for a submission to the IEEE Transactions on Network Control Systems.

We are also considering approaches from a different point of view involving the use of machine learning for easing the computational and communication burden of (more classical) model-based formation control and estimation laws. In this direction, we have submitted to the IEEE ICRA 2023 a preliminary work where we show how a network can be trained to estimate in a decentralized way the connectivity level of a group of robots by learning from an established model-based estimator. The advantage of the network is that, after a successful training, it has a much lower computational and communication complexity w.r.t. the model-based approach, and appears to scale better w.r.t. the group size. We are now studying how to extend this initial promising result to more complex multi-robot case studies.

7.2.11 Coupling Force and Vision for Controlling Robot Manipulators

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

The goal of this activity is about coupling visual and force information for advanced manipulation tasks [51]. To this end, we are exploiting the recently acquired Panda robot (see Sect. 6.2.3), 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. The use of vision in torque-controlled robots is 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).

In [38] we presented results of dynamic visual servoing for the case of moving targets while in interaction with the environment. To this end, we proposed the derivation of a feature space impedance controller for tracking a moving object as well as an Extended Kalman Filter based on the visual servoing kinematics for increasing the rate of the visual information and estimating the target velocity for both the cases of PBVS and IBVS with image point features. We validated the approach via simulations and real experiments involving a Peg-in-Hole insertion task with a moving part.

7.2.12 Deep visual servoing

Participants: Eric Marchand, Samuel Felton.

We proposed a new framework to perform VS in the latent space learned by a convolutional autoencoder. We show that this latent space avoids explicit feature extraction and tracking issues and provides a good representation, smoothing the cost function of the VS process. Besides, our experiments show that this unsupervised learning approach allows us to obtain, without labelling cost, an accurate end-positioning, often on par with the best direct visual servoing methods in terms of accuracy but with a larger convergence area. This work [15] is done in collaboration with the Lacodam team.

7.3 Haptic Cueing for Robotic Applications

7.3.1 Wearable Haptics Systems Design

Participants: Claudio Pacchierotti, Maud Marchal, Lisheng Kuang, Marco Aggravi.

We have been working on wearable haptics since few years now, both from the hardware (design of interfaces) and software (rendering and interaction techniques) points of view [52, 53].

In [30], we developed a wearable cutaneous device capable of applying lateral stretch and position/location haptic feedback to the user's skin. It is composed of a 2D Cartesian-like structure able to move a pin on the plane parallel to the skin. The pin houses a small metallic sphere of 8 mm of diameter. The sphere can be either left free to rotate when the pin moves, providing location feedback about its absolute position, or kept fixed, providing skin stretch about its relative displacement. Results of a human navigation task show an average navigation error of 0.26 m, which is comparable to state-of-the-art vibrotactile guidance techniques using two vibrating armbands. Similarly, in [31, 32], we presented a 2-degrees-of-freedom (2-DoF) hand-held haptic device for human navigation. It is composed of two platforms moving with respect to each other, actuated by two servomotors housed in one of structures. The device implements a rigid coupling mechanism between the two platforms, based on a three-legged 3-4R constrained parallel linkage, with the two servomotors actuating two of these legs. The device can apply position/kinesthetic haptic feedback to the user hand(s).

In [13], we explored the use of wearable haptics to render contacts during virtual crowd navigation. We focus on the behavioural changes occurring with or without haptic rendering during a navigation task in a dense crowd, as well as on potential after-effects introduced by the use haptic rendering. We designed an experiment (N=23) where participants navigated in a crowded virtual train station without, then with, and then again without haptic feedback of their collisions with virtual characters. Results show that providing haptic feedback improved the overall realism of the interaction, as participants more actively avoided collisions.

Finally, in the framework of H2020 project TACTILITY, we are working on designing interaction and rendering techniques for wearable electrotactile interfaces. Electrotactile feedback is provided by a system comprised of electrodes and stimulators (actuators). The electrical current travels through the subdermal area between the anode(s) and cathode(s) and stimulates the nerves endings (i.e., skin's receptors). The area of the skin where the electrode contacts the skin is stimulated, however, the sensation may be spread further when the contact point is near nerve bundles. The way electrotactile systems function is therefore completely different from mechanical and thermal tactile interfaces, as electrotactile feedback is not mediated by any skin receptor. We wrote a review paper on this topic [19], focusing on how electrotactile can be used for immersive Virtual Reality (VR) interactions.

In [20], we carried out a user study in which participants performed a standardized Fitts's law target acquisition task by using three feedback modalities: visual, visuo-electrotactile, and visuo-vibrotactile. Performance-wise, the results showed that electrotactile feedback facilitates a significantly better accuracy compared to vibrotactile and visual feedback, while vibrotactile provided the worst accuracy. Electrotactile and visual feedback enabled a comparable reaction time, while the vibrotactile offered a substantially slower reaction time than visual feedback. These outcomes highlighted the importance of (electrotactile) haptic feedback on performance, and importantly the significance of action-specific effects on spatial and time perception in VR.

In [44, 45], we proposed a tactile rendering architecture to render finger interactions in VR. We designed six electrotactile stimulation patterns/effects (EFXs) striving to render different tactile sensations. In a user study, we assessed the six EFXs in three diverse finger interactions: 1) tapping on a virtual object; 2) pressing down a virtual button; 3) sliding along a virtual surface. Results showed the importance of the coherence between the modulation and the interaction being performed and the study proved the versatility of electrotactile feedback and its efficiency in rendering different haptic information and sensations.

7.3.2 Mid-Air Haptic Feedback

Participants: Claudio Pacchierotti, Thomas Howard, Guillaume Gicquel, Maud Marchal, Lendy Mulot.

In the framework of H2020 projects H-Reality and E-TEXTURE, we have been working to develop novel mid-air haptics paradigms that can convey the information spectrum of touch sensations in the real world, motivating the need to develop new, natural interaction techniques. Both projects ended in 2022.

In [17], we investigated how to achieve sensations of continuity or gaps within tactile 2D curves rendered by ultrasound mid-air haptics (UMH). We studied the perception of pairs of amplitude-modulated focused ultrasound stimuli, investigate perceptual effects which may arise from providing simultaneous UMH stimuli, and provide perception-based rendering guidelines for generating continuous or discontinuous sensations of tactile shapes. Mean gap detection thresholds were found at 32.3 mm spacing between focal points, but a high within- and between-subject variability was observed.

In [49, 50], we presented an overview of mid-air haptic technologies for interacting in immersive environments, also analyzing the future perspectives of the field.

7.3.3 Encountered-Type Haptic Devices

Participants: Elodie Bouzbib.

Encountered-Type Haptic Displays (ETHDs) provide haptic feedback by positioning a tangible surface for the user to encounter. This allows users to freely elicit haptic feedback with a surface during a virtual simulation. ETHDs differ from most of current haptic devices which rely on an actuator always in contact with the user.

In [24], we used a Failure Mode and Effects Analysis approach to identify, organize, and analyze the failure modes and their causes in the different stages of an ETHD scenario and highlight appropriate solutions from the literature to mitigate them. We help justify these interfaces' lack of deployment, to ultimately identify guidelines for future ETHD designers.

7.3.4 Multimodal Cutaneous Haptics to Assist Navigation and Interaction in VR

Participants: Louise Devigne, Marco Aggravi, Inès Lacôte, Pierre-Antoine Cabaret, François Pasteau, Maud Marchal, Claudio Pacchierotti, Marie Babel.

Within the project Inria Challenge 9.3, we got interested on using cutaneous haptics for aiding the navigation of people with sensory disabilities. In particular, we investigated the ability of vibrotactile sensations and tap stimulations in conveying haptic motion and sensory illusions.

In [34], we investigated whether continuous mechanical stimulations, or taps, that are activated in sequence, can also create a convincing illusion of haptic motion across the skin. Moreover, we also test whether an increased curvature of the contact surface impacts the quality of the felt illusion. Results showed that the proposed "tap" stimulation was as efficient as a 120 Hz vibrotactile stimulation in conveying the haptic motion illusion. Moreover, results showed that the curvature of the contact surface had little effect on the quality of the sensation. In [33], we extended this study to investigate the discrimination of velocity changes in apparent haptic motion and the robustness of this perception, considering two stimulating sensations and two directions of motion. Results show that participants were better at discriminating the velocity of the illusory motion when comparing stimulations with higher differences in the actuators activation delay.

In [25], we designed a tangible cylindrical handle that allows interaction with virtual objects extending beyond it. The handle is fitted with a pair of vibrotactile actuators with the objective of providing in-hand spatialized cues indicating direction and distance of impacts. We evaluated its capability for rendering spatialized impacts with external virtual objects. Results show that it performs very well for conveying an impact's direction and moderately well for conveying an impact's distance to the user.

In [29], we devised a multi-modal rendering approach for the simulation of virtual moving objects inside a hollow container, based on the combination of haptic and audio cues generated by voice-coils actuators and high-fidelity headphones, respectively. Thirty participants were asked to interact with a

target cylindrical hollow object and estimate the number of moving objects inside, relying on haptic feedback only, audio feedback only, or a combination of both. Results indicate that the combination of various senses is important in the perception of the content of a container.

The use of a mobility aid can be challenging for people with both motor and visual impairment. In order to help them increase their autonomy, we proposed in [28] to design an adapted feedback through vibrotactile handles adaptable to any walker, by indicating the proximity of obstacles on the way of the user. We conducted a technical validation study on 14 able-bodied blindfolded participants. The objective was to perform without collisions and as fast as possible on a circuit. Through a specific user study, we collected user feedback after 2 months of daily-life use by a blind end-user with cerebellar syndrom. Results show a major improvement of the safety of navigation.

7.3.5 Digital Twins for robotics

Participants: Claudio Pacchierotti.

Among the most recent enabling technologies, Digital Twins (DTs) emerge as data-intensive network-based computing solutions in multiple domains—from Industry 4.0 to Connected Health. A DT works as a virtual system for replicating, monitoring, predicting, and improving the processes and the features of a physical system – the Physical Twin (PT), connected in real-time with its DT. Such a technology, based on advances in fields like the Internet of Things (IoT) and machine learning, proposes novel ways to face the issues of complex systems as in Human-Robot Interaction (HRI) domains.

In [11], we proposed a physical-digital twinning approach to improve the understanding and the management of the PT in contexts of HRI according to the interdisciplinary perspective of neuroergonomics.

7.4 Shared Control Architectures

7.4.1 Shared Control for Multiple Robots

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

Following our previous works on flexible formation control of multiple robots with global requirements, in particular connectivity maintenance, in [10] we have instead presented a decentralized haptic-enabled connectivity-maintenance control framework for heterogeneous human-robot teams. The proposed framework controls the coordinated motion of a team consisting of mobile robots and one human, for collaboratively achieving various exploration and SAR tasks. The human user physically becomes part of the team, moving in the same environment than the robots, while receiving rich haptic feedback about the team connectivity and the direction toward a safe path. We carried out human subjects studies, both in simulated and real environments. The results showed that the proposed approach is effective and viable in a wide range of scenarios.

7.4.2 Shared Control for Virtual Character Animation

Participants: Claudio Pacchierotti.

Shared control techniques can also be used to adapt the motion of virtual characters to respond to some external stimuli, e.g., the motion of the user's avatar.

In [18], we proposed the design of viewpoint-dependent motion warping units that perform autonomous subtle updates on animations through the specification of visual motion features such as visibility, or spatial extent. We express the problem as a specific case of visual servoing, where the warping of a given character motion is regulated by a number of visual features to enforce. Results demonstrate

Figure 8: A participant drives our smart power wheelchair in musée des Beaux Arts in Rennes.

the relevance of the approach for different motion editing tasks and its potential to empower virtual characters with attention-aware communication abilities. The effects of non-verbal communication was then studied more in depth in [40], where we investigate the role of gazing in VR.

7.4.3   Shared Control of a Wheelchair for Navigation Assistance

Participants: Louise Devigne, François Pasteau, Marie Babel.

Power wheelchairs allow people with motor disabilities to have more mobility and independence. In order to improve the access to mobility for people with disabilities, we previously designed a semi-autonomous assistive wheelchair system which progressively corrects the trajectory as the user manually drives the wheelchair and smoothly avoids obstacles.

Ecologicals experiment have been conducted in two museums, Musée des beaux Arts and Musée de Bretagne, both in Rennes [48, 54]. During the experiments, a sample of 20 powered wheelchair users composed of expert users as well as users experiencing high difficulties while steering a wheelchair, were asked to visit a museum during one hour using a powered wheelchair equipped with a driving assistance module. Some users were accompanied with their relatives. We clearly confirmed the excellent ability of the system to assist users in an ecological environnement as well as the beneficial effect on their relatives induced by their awareness of the user and surrounding safety. Results show that usability and learning are very good as well as usefulness. The social dimensions and the use intention were good, indicating a propensity of the users to use the device. Other studies are underway, particularly in elderly care facilities.

Despite the COVID situation, INSA and the rehabilitation center of Pôle Saint Hélier managed to co-organize clinical trials in July 2022 at INSA. The idea is to evaluate the benefice of a driving assistance module for powered wheelchair taking into accoung negative obstacles such as curbs or potholes. 18 wheelchair users experiencing high driving difficulties participated to the trials. We confirmed the

Figure 9: A participant drives our smart power wheelchair on a curb during clinical trials.

ability of the system to efficiently assist users and the relevant usage of such an assistive technology in a controlled environment. These results should be completed by an additional clinical trial.

As a final result related to the ADAPT project, [21] describes the robotic assistive technologies developed for users of electrically-powered wheelchairs. We detailed our work and our various collaborations with our scientific and medical partners, as well as the validation of co-developped systems through extensive experimental campaigns and large-scale clinical trials.

7.4.4   Style Transfer for Robotics

Participants: Paolo Robuffo Giordano, Claudio Pacchierotti, Raul Fernandez Fernandez.

Neural Style Transfer (NST) was originally proposed to define the Content and Style of an image using neural networks. For example, it was used to define the Content as the elements represented in a painting (e.g., people, animals, houses), and the Style as the low-level features specific to the artist (e.g., vivid colors, long brushstrokes). NST allows the definition of a high-level layer of abstraction that can extend the same definition of Content and Style in a larger range of applications, including robotic motion. Here the Content can be defined as the movements performed by the robot (e.g., moving forward, walk in circles, move sideways) and the Style as the emotion/style conveyed by these movements.

In [26], we proposed a custom NST framework for transferring a set of styles to the motion of a robotic manipulator, e.g., the same robotic task can be carried out in an "angry", "happy", "calm", or "sad" way. An autoencoder architecture extracts and defines the Content and the Style of the target robot motions. A Twin Delayed Deep Deterministic Policy Gradient (TD3) network generates the robot control policy using the loss defined by the autoencoder. The proposed Neural Policy Style Transfer TD3 (NPST33) alters the robot motion by introducing the trained style. The considered styles can be learned online from human demonstrations. We carried out an evaluation with human subjects, asking them to recognize the style behind some representative robotic motions. Results show a good recognition rate (always greater than 50%), proving that it is possible to convey different styles to a robot using this approach.

7.4.5   Multisensory power wheelchair simulator

Participants: Sylvain Guegan, Louise Devigne, François Pasteau, Marie Babel.

Power wheelchairs are one of the main solutions for people with reduced mobility to maintain or regain autonomy and a comfortable and fulfilling life. However, driving a power wheelchair in a safe way is a difficult task that often requires training methods based on real-life situations. Although these methods are widely used in occupational therapy, they are often too complex to implement and unsuitable for some people with major difficulties.

In this context, we collaborated with clinicians to develop a Virtual Reality based power wheelchair simulator. This simulator is an innovative training tool adapted to any type of situations and impairments. 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. A clinical trial has been conducted in May 2021 and October 2021 in which 26 power wheelchair regular users were asked to complete a clinically validated task designed by clinicians within four display conditions: using the HTC Vive Pro HMD, Immersia immersive room or a screen (with or without haptic and vestibular feedback). The objective of this study was to compare performances between the four conditions and to evaluate the Quality of Experience. First analyses clearly show that immersive conditions allow high driving performances to be achieved [21].

We acquired a mini immersive room in order to perform trials in clinical structures. We are currently preparing clinical trials and ethics committee (Comité de Protection des Personnes) procedures to evaluate the clinical benefit of the long-term use of this simulator.

7.4.6   Integrating social interaction in a VR powered wheelchair driving simulator

Participants: Emilie Leblong, Antoine Cellier, Maud Marchal, François Pasteau, Marie Babel.

Navigating in the city while driving a powered wheelchair, in a complex and dynamic environment made of various interactions with other humans, can be challenging for a person with disabilities. Learning how to drive a powered wheelchair remains then a major issue for the clinical teams prescribing these technical mobility aids. The work carried out as part of the Interreg ADAPT project has made it possible to design a powered wheelchair simulator in VR. This work is done in cooperation with Anne-Hélène Olivier (MimeTIC team).

To promote the transfer of skills from virtual to real, the use of such a platform requires the deployment of environmentally friendly interactive populated virtual environments. These are currently empty of any pedestrians, even though the question of social interaction in the framework of an inclusive urban mobility is fundamental.

The objective is to better understand how pedestrians and powered wheelchair users interact. New models of interaction will be used to improve dynamic virtual environments by including virtual humans that faithfully reproduce the behaviors modeled in terms of the simulator user's reaction in a handicap situation.

A trial (ethical agreements obtained from COERLE and CHU Rennes) has been organized within the Musée de Bretagne and Musée des Beaux Arts (museums of Rennes), where we observed limited interactions [47]. We also analyzed previously collected data and started to propose a model of joint walker and wheelchair user behavior.

8   Bilateral contracts and grants with industry

8.1   Bilateral contracts with industry

IRT JV Happy

Figure 10: Participant driving in a virtual environment with our simulator

> **Participant:**   François Chaumette.

No Inria Rennes 13521, duration: 72 months.

F. Chaumette is in secondment (at 20%) at IRT Jules Verne in Nantes since 2018. This year, he was involved in the projects Fetch with EDF, Incabot with Airbus, and Happy 2 with Airbus & Naval group to give his expertise in visual servoing and to develop basic software with ViSP. He is also co-author with G. Chabert and A. Suarez-Roos (IRT Jules Verne) of a patent about "Procédé d'assemblage automatisé de deux pièces comprenant un asservissement avec des caméras" (ref FR22 07293) that has been developed in the scope of the Happy project.

Airbus React

> **Participants:**   Julien Dufour, Romain Lagneau, Fabien Spindler, François Chaumette.

No Inria Rennes 16165, duration: 24 months.

This project started in September 2021. It is in collaboration with Laas in Toulouse for Airbus in Saint Nazaire and Toulouse. Its goal is to develop a vision-based localization system so that a robot arm is able to point accurately on an aircraft panel.

8.2   Bilateral grants with industry

Creative

> **Participants:**   Thibault Noël, François Chaumette, Eric Marchand.

No Inria Rennes 2022000032, duration: 36 months.

This project funded by Creative started in October 2021. It supports Thibault Noël's PhD who benefits from a CIFRE grant (see Section 7.2.6).

IRT JV Perform

> **Participant:**   François Chaumette.

No Inria Rennes 16107, duration: 36 months.

This project funded by IRT Jules Verne started in November 2021. It is achieved in cooperation with Stéphane Caro from LS2N in Nantes to support Thomas Rousseau's PhD at IRT Jules Verne about visual servoing of cable-driven parallel robots

MX

> **Participants:**   François Pasteau, Marie Babel, Sylvain Guegan.

INSA Rennes, duration: July 2020 - June 2022.

This contract with MX (Acigné) aimed to define an online load estimation in order to servo truck loaders.

Sopra-Steria

> **Participants:**   François Pasteau, Marie Babel, Sylvain Guegan, Fabien Grzeskowiak.

INSA Rennes, duration: 12 months. This project funded by Sopra Steria aimed to design a smart rollator equiped with haptic feedback.

9   Partnerships and cooperations

9.1   International initiatives

9.1.1   Inria associate team not involved in an IIL or an international program

FRANTIC

Title: French-Russian Advanced and Novel TactIle Cyberworlds

Duration: 2021 -> 2022

Coordinator: Dzmitry Tsetserukou (D.Tsetserukou@skoltech.ru)

Partners:

- Skolkovo institute of science and technology (Russie)

Inria contact: Claudio Pacchierotti

Local Members: Claudio Pacchierotti, Paolo Robuffo Giordano, Anatole Lécuyer, Elodie Bouzbib

Summary: Touch is an essential component of any human experience. Despite its importance, nowadays interactions with cyberphysical worlds are rarely capable of providing any meaningful haptic sensation to the human user, limiting their experience to vision and audio stimuli. Indeed, to attain compelling touch interactions with cyberphysical systems, we still need to achieve a wide range of theoretical and technological advancements in haptic rendering and interaction techniques, as well as innovative designs of haptic devices and an increased comprehension of human perception. We want to leverage the experience of Inria and Skoltech in designing haptic interfaces and rendering algorithms for immersive environments to finally bring compelling haptic sensations in this world, addressing applications of eXtended Reality and teleoperation of mobile robots as example of the potential of versatility of these feedback systems.

ISI4NAVE

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

Duration: 2019 -> 2022

Coordinator: Tom Carlson (t.carlson@ucl.ac.uk)

Partners:

- University College London London (Royaume-Uni)

Inria contact: Marie Babel

Local Members: Marie Babel, Claudio Pacchierotti, Emilie Leblong, François Pasteau

Summary: 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 sensori-motor 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.

9.1.2   Participation in other International Programs

GentleMAN

Participants: Fouad Makiyeh, Alexandre Krupa, François Chaumette, Fabien Spindler.

Title: Gentle and Advanced Robotic Manipulation of 3D Compliant Objects

Duration: August 2019 - December 2023

Coordinator: Sintef Ocean (Norway)

Partners:

- Sintef Ocean (Norway)
- NTNU (Norway)
- NMBU (Norway)
- MIT (USA)
- QUT (Australia)

Inria contact: Alexandre Krupa

Summary: This project is granted by The Research Council of Norway. Its main objective is to develop a novel learning framework that uses visual, force and tactile sensing to develop new multi-modal learning models to enable robots to learn new and advanced skills for the manipulation of 3D compliant objects. The Rainbow group is involved in the elaboration of new approaches for visual tracking of deformable objects, active vision perception and visual servoing for deforming soft objects into desired shape (see Section 7.2.7).

BIFROST

> **Participants:** Mandela Ouafo Fonkoua, Fouad Makiyeh, Alexandre Krupa, François Chaumette, Fabien Spindler.

Title: A Visual-Tactile Perception and Control Framework for Advanced Manipulation of 3D Compliant Objects

Duration: July 2021 - December 2025

Coordinator: Sintef Ocean (Norway)

Partners:

- Sintef Ocean (Norway)
- MIT (USA)

Inria contact: Alexandre Krupa

Summary: This project is granted by The Research Council of Norway. Its main objective is to develop a visual-tactile perception and Control framework for advanced manipulation of 3D compliant objects. The Rainbow group is in charge of elaborating novel visual servoing approaches fusing visual and tactile feedback for dexterous manipulation of soft objects.

9.2 European initiatives

9.2.1 Horizon Europe

REGO [REGO project on cordis.europa.eu]

> **Participants:** Claudio Pacchierotti, Paolo Robuffo Giordano, François Chaumette, Alexandre Krupa, Fabien Spindler.

Title: Cognitive robotic tools for human-centered small-scale multi-robot operations

Duration: From October 1, 2022 to September 30, 2026

Partners:

- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France
- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- UNIVERSITEIT TWENTE, The Netherlands
- CENTRE HOSPITALIER UNIVERSITAIRE DE RENNES, France
- SCUOLA SUPERIORE DI STUDI UNIVERSITARI E DI PERFEZIONAMENTO S ANNA, Italy
- FONDAZIONE ISTITUTO ITALIANO DI TECNOLOGIA, Italy
- HAPTION SA, France
- HELMHOLTZ-ZENTRUM DRESDEN-ROSSENDORF EV, Germany

Coordinator: Claudio Pacchierotti

Summary: Robots are still often regarded as large machines with links, gears, and electric motors, autonomously interacting with the surrounding environment. Despite the great research efforts in robotics and human-robot interaction (HRI), the way we design, use, and control robots has not fundamentally changed in the past 20 years. We see in small-scale wireless multi-robot systems and cognitive HRI a revolutionary answer to nowadays robots limitations. Instead of large, tethered machines, that are difficult for the human user to control, REGO proposes an innovative set of AI-powered, modular, microsized swarms of robots. They are wirelessly steered by electromagnetic fields as well as able to react to other external stimuli, and then naturally controlled by humans through intuitive dexterous interfaces and interaction techniques. Taking advantage of AI multi-robot control strategies, these robots can team up and collaborate to fulfill complex tasks in a robust and unprecedented flexible way. By exploiting multisensory interaction techniques and cognitive shared control, the operator will achieve an unparalleled level of seamless interaction and continuous collaboration with the robotic team. According to the application at hand, the robotic team will feature different task-specific characteristics (e.g. biocompatibility for medical procedures, biodenitrification for cleaning water, ability to carry drugs to fight infections) and be dispatched through various delivery systems, including a stimuli-responsive milli-scale wireless robotic carrier developed within the project. To achieve this revolution, REGO will develop magnetic multi-robot motion control systems, autonomous swarm control techniques for micro-sized robots, human-robot haptic-centered interfaces, and cognitive shared-control techniques. REGO enables the next generation of AI-powered interactive small-size multi-robots systems, with increased capabilities to work with each other and their human operators.

9.2.2 H2020 projects

H-Reality   [H-Reality project on cordis.europa.eu]

Participants: Claudio Pacchierotti, Maud Marchal.

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

Duration: From October 1, 2018 to March 31, 2022

Partners:

- THE UNIVERSITY OF BIRMINGHAM, United Kingdom
- ULTRALEAP LIMITED, United Kingdom
- ACTRONIKA, France
- TECHNISCHE UNIVERSITEIT DELFT, The Netherlands
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France
- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE RENNES, France

Inria contact: Claudio Pacchierotti

Coordinator: Mike Adams

Summary: "Touch comes before sight, before speech. It is the first language and the last, and it always tells the truth" (Margaret Atwood), yet 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.

TACTILITY   [TACTILITY project on cordis.europa.eu]

> **Participants:**   Claudio Pacchierotti, Maud Marchal.

Title: TACTIle feedback enriched virtual interaction through virtual realITY and beyond

Duration: From July 1, 2019 to September 30, 2022

Partners:

- FUNDACION TECNALIA RESEARCH & INNOVATION, Spain
- AALBORG UNIVERSITET, Denmark
- UNIVERSITA DEGLI STUDI DI GENOVA, Italy
- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE, France
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France
- INSTITUT NATIONAL DES SCIENCES APPLIQUEES DE RENNES, France
- UNIVERSITAT DE VALENCIA, Spain
- TECNALIA SERBIA DOO BEOGRAD, Serbia
- MANUS MACHINAE BV, The Netherlands
- SMARTEX SRL, Italy
- IMMERSION, France

Inria contact: Ferran Argelaguet

Coordinator: Thierry Keller

Summary: Haptic technologies have recreated the sense of touch by mechanical or electrical means to provide immersive experiences. Applications range from video games and virtual reality to robotics and medical research. The EU-funded TACTILITY project is developing the next generation of interactive systems that will enhance users' sense of immersion. It is conducting cutting-edge research on transcutaneous stimulation, textile-based multi-pad electrodes and electronic skin. If successful, the project will enable a high-fidelity experience through low-cost and user-friendly wearable technology.

E-TEXTURES   [E-TEXTURES project on cordis.europa.eu]

> **Participants:**   Maud Marchal, Claudio Pacchierotti.

Title: AI-Enabled Mid-Air Haptic Texture Generation

Duration: From April 1, 2021 to June 30, 2022

Partners:

- ULTRALEAP LIMITED, United Kingdom
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS, France

Inria contact: Maud Marchal

Coordinator: Orestis Georgiou

Summary: Virtual interactions and digitalisation improve many aspects of daily life, enabling easy execution of a myriad of tasks from our desktops. But touch is still not part of this picture. The H-Reality project developed a novel haptic algorithm that uses AI and a series of phased ultrasonic waves to create textured holograms that you can touch and feel in mid-air. The EU-funded E-Textures project will focus on commercialisation of the mid-air haptic texture generation technology for real-time virtual touch interactions in digital signage for advertising markets and businesses, such as garments retail and healthcare. The consortium, which comprises experts in mid-air haptics, market research and technology innovation, and 3D interaction techniques is uniquely positioned to achieve this objective.

GuestXR   [GuestXR project on cordis.europa.eu]

> **Participants:**   Claudio Pacchierotti.

Title: GuestXR: A Machine Learning Agent for Social Harmony in eXtended Reality

Duration: From January 1, 2022 to December 31, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- UNIWERSYTET WARSZAWSKI (UNIWARSAW), Poland
- VIRTUAL BODYWORKS SL (Virtual Bodyworks S.L.), Spain
- UNIVERSITEIT MAASTRICHT, Netherlands
- UNIVERSITAT DE BARCELONA (UB), Spain
- FUNDACIO EURECAT (EURECAT), Spain
- REICHMAN UNIVERSITY (REICHMAN UNIVERSITY), Israel
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (CNRS), France
- G.TEC MEDICAL ENGINEERING GMBH (G.TEC MEDICAL ENGINEERING GMBH), Austria

Inria contact: Anatole LECUYER

Coordinator: Simona Neri

Summary: Immersive online social spaces will soon become ubiquitous. However, there is also a warning that we need to heed from social media. User content is the 'lifeblood of social media'. However, it often stimulates antisocial interaction and abuse, ultimately posing a danger to vulnerable adults, teenagers, and children. In the VR space this is backed up by the experience of current virtual shared spaces. While they have many positive aspects, they have also become a space full of abuse. Our vision is to develop GuestXR, a socially interactive multisensory platform system that uses eXtended Reality (virtual and augmented reality) as the medium to bring people together for immersive, synchronous face-to-face interaction with positive social outcomes. The critical innovation is the intervention of artificial agents that learn over time to help the virtual social gathering realise its aims. This is an agent that we refer to as "The Guest" that exploits Machine Learning to learn how to facilitate the meeting towards specific outcomes. Underpinning this is neuroscience and social psychology research on group behaviour, which will deliver rules to Agent Based Models (ABM). The combination of AI with immersive systems (including haptics and immersive audio), virtual and augmented reality will be a hugely challenging research task, given the vagaries of social meetings and individual behaviour. Several proof of concept applications will be developed during the project, including a conflict resolution application in collaboration with the UN. A strong User Group made up of a diverse range of stakeholders from industry, academia, government and broader society will provide continuous feedback. An Open Call will be held to bring in artistic support and additional use cases from wider society. Significant work is dedicated to ethics "by design", to identify problems and look eventually towards an appropriate regulatory framework for such socially interactive systems.

9.2.3   Other european programs/initiatives

Interreg VA France (Channel) England ADAPT

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

Title: Assistive Devices for empowering disAbled People through robotic Technologies

Duration: Jan 2017 - June 2022

Coordinators: ESIGELEC/IRSEEM Rouen

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),
- CornwallMobility Center (UK)

Inria contact: Marie Babel

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

9.3   National initiatives

Equipex+ Tirrex

Participants: Fabien Spindler, François Chaumette.

no Inria Rennes OIP 03-22-01, duration: 8 years.

This large project devoted to open robotics platforms started in December 2021. Rainbow is responsible of the manipulation axis for which a new M4 platform (Multi-arm Multi-sensor Mobile Manipulator) will be designed and installed in our lab. This year, we wrote the specifications of this platform and started the negotiations with potential suppliers.

PEPR O2R

Participants: Maud Marchal, Marie Babel, Claudio Pacchierotti, Marco Tognon.

duration: 8 years.

The Organic Robotics program proposes to implement a responsible and socially acceptable robotics. This PEPR will intensify the multidisciplinary approach of the community (digital, life sciences, engineering, environmental, social sciences) in a strategy that radically differs from the current vision of robotics and its limitations. The Organic Robotics program therefore aims to initiate a shift in robotics allowing to create a new generation of robots capable of interacting and working in symbiosis with humans. We propose to consider the robot, no longer as an automation machine, but as a tool, in line with those that humans have created, used and optimized in order to explore and act on their environment. More efficient, modular, reconfigurable and adaptive, organic robots will become an extension of humans. The PEPR O2R will start in September 2023. M. Marchal has contributed to the proposal writing and is a member of the executive committee.

PEPR eNSEMBLE

Participants: Maud Marchal.

duration: 8 years.

The purpose of eNSEMBLE (Future of Digital Collaboration) is to fundamentally redefine digital tools for collaboration. To address this challenge, a paradigm shift in the design of collaborative systems is needed, comparable to the one that saw the advent of personal computing. To collaborate in a fluid and natural way while taking advantage of computer capabilities, collaboration and sharing must become native features of computer systems, in the same way that files or applications are today. To achieve this goal, we need to invent mixed (i.e. physical and digital) collaboration spaces that do not simply replicate the physical world in virtual environments, enabling co-located and/or geographically distributed teams to work together smoothly and efficiently. The PEPR eNSEMBLE will start in September 2023. M. Marchal has contributed to the writing of the proposal.

ANR Marsurg

Participants:	Eric Marchand, François Chaumette, Fabien Spindler.

no Inria 16162, duration: 48 months.

This project started in September 2021. It involves a consortium managed by ISIR (Paris) with Pixee Medical and Rainbow group. It aims at researching markerless augmented reality solution for orthopedic surgery

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 (see Section 7.2.3)

Inria Challenge DORNELL

Participants:	Marie Babel, Claudio Pacchierotti, Maud Marchal, François Pasteau, Sylvain Guegan, Louise Devigne, Marco Aggravi, Inès Lacôte, Pierre-Antoine Cabaret, Lisheng Kuang.

Title: DORNELL: A multimodal, shapeable haptic handle for mobility assistance of people with disabilities

Duration: November 2020 - December 2024

Coordinators: Marie Babel, Claudio Pacchierotti

Partners:

- Potioc Inria team
- MFX Inria team
- LGCGM (Rennes)
- Centre de rééducation Pôle Saint Hélier (Rennes)
- ISIR (Paris)
- Institut des jeunes aveugles (Yzeure)

Inria contact: Marie Babel, Claudio Pacchierotti

Summary: While technology helps people to compensate for a broad set of mobility impairments, visual perception and/or cognitive deficiencies still significantly affect their ability to move safely and easily. We propose an innovative multisensory, multimodal, smart haptic handle that can be easily plugged onto a wide range of mobility aids, including white canes, precanes, walkers, and power wheelchairs. Specifically fabricated to fit the needs of a person, it provides a wide set of ungrounded tactile sensations (e.g., pressure, skin stretch, vibrations) in a portable and plug-and-play format –

bringing haptics in assistive technologies all at once. The project will address important scientific and technological challenges, including the study of multisensory perception, the use of new materials for multimodal haptic feedback, and the development of a haptic rendering API to adapt the feedback to different assistive scenarios and user's wishes. We will co-design DORNELL with users and therapists, driving our development by their expectations and needs.

BPI Lichie

Participants:	Maxime Robic, John Thomas, Julien Dufour, Eric Marchand, François Chaumette.

no Inria 14876, duration: 45 months.

This project started in March 2020. It involves a consortium managed by Airbus Defense and Space (Toulouse) with many companies, Onera and Inria. It aims at designing a new constellation of satellites with on-board imaging facilities. Robotics for the assembly of the satellites is also studied. As for Rainbow, this project funds Maxime Robic and John Thomas PhDs (see Sections 7.2.4 and 7.2.5, as well as the software developments achieved for ViSP by Julien Dufour.

ANR CAMP

Participants:	Paolo Robuffo Giordano, Fabien Spindler.

Title: Intrinsically-Robust and Control-Aware Motion Planning for Robots in Real-World Conditions

Duration: October 2020 - September 2024

Coordinator: P. Robuffo Giordano

Partners:

- LAAS (Toulouse)
- Univ. Twente (Netherlands)

Inria contact: P. Robuffo Giordano

Summary: An effective way of dealing with the complexity of robots operating in real (uncertain) environments is the paradigm of "feedforward/feedback" or "planning/control": in a first step a suitable nominal trajectory (feedforward) for the robot states/controls is planned exploiting the available information (e.g., a model of the robot and of the environment). While there has been an effort in proposing "robust planners" or more "global controllers" (e.g., Model Predictive Control (MPC)), a truly unified approach that fully exploits the techniques of the motion planning and control/estimation communities is still missing and the existing state-of-the-art has several important limitations, namely (1) lack of generality, (2) lack of computational efficiency, and (3) poor robustness. In this respect, the ambition of CAMP is to (1) develop a general and unified "intrinsically-robust and control-aware motion planning framework" able to address all the above-mentioned issues, and to (2) demonstrate the applicability of this new framework to real robots in real-world challenging tasks. In particular we envisage two robotics demonstrators for showing at best the effectiveness and generality of our methodology: (1) an indoor pick- and-place/assembly task involving a 7-dof torque-controlled arm for a first validation in "controlled conditions" and (2) an outdoor cooperative mobile manipulation task involving an aerial manipulator (a quadrotor UAV equipped with an onboard arm) and a skid-steering mobile robot with an onboard arm for a final validation in much less favorable experimental conditions (see Sect. 7.2.1)

ANR MULTISHARED

Participants:	Paolo Robuffo Giordano, Claudio Pacchierotti, Vincent Drevelle, Julien Pettré.

Title: Shared-Control Algorithms for Human/Multi-Robot Cooperation

Duration: September 2020 - August 2024

Coordinator: P. Robuffo Giordano

Inria contact: P. Robuffo Giordano

Summary: The goal of the Chaire AI MULTISHARED is to significantly advance the state-of-the-art in multi-robot autonomy and human-multi-robot interaction for allowing a human operator to intuitively control the coordinated motion of a multi-UAV group navigating in remote environments, with a strong emphasis on the division of roles between multi-robot autonomy (in controlling its motion/configuration and online decision-making) and human intervention/guidance for providing high-level commands to the group while being most aware of the group status via VR and haptics technology (see Sect. 7.1.1 and Sect. 7.2.10).

9.4 Regional initiatives

CominLabs MAMBO

Participants:	Lev Smolentsev, Alexandre Krupa, François Chaumette, Paolo Robuffo Giordano, Fabien Spindler.

Title: Manipulation of Soft Bodies with Multiple Drones

Duration: October 2020 - September 2024

Coordinator: LS2N (Nantes)

Partners:

- LS2N (Nantes)

Inria contact: Alexandre Krupa

Summary: This project is funded by the Labex CominLabs. It is led by the ARMEN team at LS2N (Nantes) and implies the collaboration of the Rainbow Project-Team. Its objective is to propose a scientific framework for allowing the manipulation of an object by the combined action of two drones equipped with onboard cameras and force sensors. The envisaged solution is to manipulate a deformable body (a slender beam) attached between the two drones in order to grasp an object on the floor and move it to another location. In the scope of this project, the Rainbow group is involved in the elaboration of new approaches for controlling the 2 drones by visual servoing using data provided by onboard RGB-D cameras (see Section 7.2.9).

Ambrougerien

Participants: Marie Babel, Vincent Drevelle, François Pasteau, Merwane Bouri.

Title: Autonomie, MoBilité et fauteuil ROUlant robotisé : GEolocalisation indoor et Recharge IntelligENte

Duration: December 2020 - December 2024

Coordinator: DK Innovation (Plérin)

Partners:

- INSA Rennes
- Hoppen (Rennes)
- Centre de médecine physique et de réadaptation Pôle Saint Hélier (Rennes)

Inria contact: Marie Babel

Summary: This project started in December 2020 and is supported by Brittany region and Rennes Métropole. AMBROUGERIEN aims at supporting the independence of people in electric wheelchairs. A dedicated interface allows the wheelchair to move autonomously to secure the transfer and to return to an intelligent induction recharging base. Information on the internal state of the wheelchairs facilitates fleet management.

Academic Chair IH2A

Participants: Marie Babel, Vincent Drevelle, Maud Marchal, Claudio Pacchierotti, François Pasteau, Louise Devigne, Fabien Grzeskowiak, Guillaume Vailland, Anne-Hélène Olivier (MimeTIC), Bruno Arnaldi (Hybrid), Valérie Gouranton (Hybrid), Florian Nouviale (Hybrid), Alexandre Audinot (Hybrid).

Title: Academic Chair on Innovations, Handicap, Autonomy and Accessibility (IH2A)

Duration: September 2020 -

Coordinator: Marie Babel

Partners:

- IETR Rennes
- LGCGM Rennes
- Centre de médecine physique et de réadaptation Pôle Saint Hélier (Rennes)

Inria contact: Marie Babel

Summary: This research chair (Innovations, Handicap, Autonomy and Accessibility - IH2A) is a continuation of the research work developed at INSA Rennes/Rainbow team on assistive robotics. The idea is to propose the most suitable technological solutions to compensate for sensory-motor handicaps limiting the mobility and autonomy of people in daily life tasks and leisure activities. The Chair thus aims at perpetuating these activities, both from a societal point of view and from a scientific and clinical point of view, and is intended to be an effective and innovative tool for the deployment of large-scale research in this area. The creation of a new type of multidisciplinary and innovative collaborative site of experimentations will allow the clinical and scientific validation of the technical assistance offered, while ensuring the accessibility of the solutions deployed.

10 Dissemination

Participants: Paolo Robuffo Giordano, François Chaumette, Alexandre Krupa, Claudio Pacchierotti, Marco Tognon, Marie Babel, Quentin Delamare, Vincent Drevelle, Sylvain Guegan, Maud Marchal, Éric Marchand.

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Member of the organizing committees

- C. Pacchierotti: Cross-Cutting Challenge Chair, IEEE Haptics Symposium (HAPTICS), Santa Barbara, USA.

10.1.2 Scientific events: selection

Program chair

- M. Marchal was Program Chair of EuroXR International Conference.

Member of the conference program committees

- C. Pacchierotti: Conference Editorial Board, Eurohaptics Conference, Hamburg, Germany.

- P. Robuffo Giordano and Marie Babel were Associate Editor for IEEE ICRA 2023

- M. Marchal was Committee member of IEEE ISMAR Doctorial Consortium, Program Committee Member of ACM/Eurographics Symposium on Computer Animation, Program Committee Member of European Tangible Interaction Studio, IEEE Virtual Reality Award Committee, ACM Virtual Reality Symposium Award Committee.

Reviewer

- F. Chaumette: ECC(1)

- A. Krupa: IEEE/RSJ IROS (1), IEEE ICRA (1)

- C. Pacchierotti: IEEE ICRA (2), IEEE VR (2)

- P. Robuffo Giordano: HFR (1), IEEE ICRA (1),

- E. Marchand: IEEE ICRA (1), IEEE IROS (2)

- M. Marchal: IEEE ISMAR (2)

- M. Babel: IEEE ICORR (1)

10.1.3 Journal

Member of the editorial boards

- P. Robuffo Giordano and F. Chaumette are Editors for the IEEE Transactions on Robotics

- E. Marchand is a Senior Editor of IEEE Robotics ans Automation Letters

- C. Pacchierotti is Associate Editor for the IEEE Robotics and Automation Letters (RA-L). He was also Guest co-editor of IEEE Transactions on Haptics for the Special Issue "Haptics in the metaverse: Haptic feedback for Virtual, Augmented, Mixed, and eXtended Realities"

- A. Krupa was Associate Editor for the IEEE Transactions on Robotics until June 2022

- M. Marchal is Associate Editor of IEEE Transactions on Visualization and Computer Graphics, IEEE Transactions on Haptics, ACM Transactions on Applied Perception, IEEE Computer Graphics and Applications, Computers & Graphics

- M. Babel is Associate Editor of Springer Social Robotics.

Reviewer - reviewing activities

- F. Chaumette: IEEE RA-L (2)

- A. Krupa: IEEE RA-L (3)

- C. Pacchierotti: IEEE Trans. Haptics (4), Frontiers in Virtual Reality (1), IEEE Trans. Human-Machine Systems (1), APL bioengineering (1)

- V. Drevelle: IEEE RA-L (1)

- M. Marchal: ACM Trans. on Graphics (1), IEEE Trans. Haptics (1), IEEE TVCG (1)

10.1.4 Invited talks

- C. Pacchierotti. "Haptics: technology and perspectives."Workshop on "Frontiers in Haptic Technology and Interaction Design: the Challenges, the Technology, the Perspectives" at NordCHI, Aarhus, Denmark, 2022.

- C. Pacchierotti. "Haptic-enabled robotic systems for manipulating soft materials." Workshop on "Grasping and manipulation of deformable objects" at I-RIM, Rome, Italy, 2022.

- C. Pacchierotti. "Cutaneous haptics for the metaverse." University of Aarhus, Herning, Denmark, 2022.

- C. Pacchierotti. "Cutaneous haptic feedback for robotics and Virtual Reality." University of Rome "La Sapienza", Rome, Italy, 2022.

- C. Pacchierotti. "Cutaneous haptic feedback for robotics and Virtual Reality." Laboratoire d'Informatique de Grenoble – UMR 5217, Grenoble (then held online), France, 2022.

- P. Robuffo Giordano. "Shared Control for Tele-manipulation and Tele-navigation". KTH, Sweden, August 2022

- P. Robuffo Giordano. "An introduction to rigidity theory for localization and formation control of multiple robots". ECC2022 workshop on "Rigidity Theory applied to Dynamic Systems from Parallel Robots to Multi-Agent Formations", July 2022

- F. Chaumette. "Geometric and End-to-End Robot Vision-based Control". Inria Paris, December 2022

- M. Marchal "Implementing the sense of touch in VR". French Ambassady in Australia, March 2022.

- M. Marchal "Women in XR", Panelist of ACM SUI, November 2022.

10.1.5 Leadership within the scientific community

- F. Chaumette is a member of the "Haut Comité des Infrastructures de Recherche" of the French Ministery of Research. He also serves as a member of the Scientific Council of the Mathematics and Computer Science Department of INRAE. He is also a founding member of the Scientific Council of the GdR Robotique.

- C. Pacchierotti: Senior Chair, IEEE Technical Committee on Haptics; Secretary, Eurohaptics Society; Chair, Eurohaptics Best PhD Thesis Award.

- M. Marchal is Vice-Director of GDG IG-RV; Chair of IEEE VGTC Best VR Dissertation Award Committee; Member of the Board of Institut Universitaire de France; Member of the Executive Committee of PEPR O2R.

10.1.6 Scientific expertise

- P. Robuffo Giordano is member (elected) of the Section 07 of the Comité National de la Recherche Scientifique. He also served as expert/reviewer for the euRobotics "George Giralt" award for the best European PhD thesis in robotics, for evaluating research projects from the SNSF (Switzerland) and Advanced Grants from the ERC. He was reviewer for the H2020 projects ACROBA, Aerial-Core and HyFliers

- A. Krupa and P. Robuffo Giordano served as expert/reviewer for the Best French PhD Thesis in robotics awarded by the GdR Robotique in 2022.

- F. Chaumette served as member of the IEEE RAS Fellow Nomination Committee and as member of the Scientific Council of LAAS/Airbus joint lab ROB4FAM.

- Marie Babel serves since 2017 as an expert for the International Mission of the French Research Ministry (MEIRIES).

- M. Babel served as a member of the Selection and Validation Committee of the Pôle Images et Réseaux.

10.1.7 Research administration

- F.Chaumette is a member of the Inria COERLE committee (in charge of the ethical aspects of all Inria research). He also evaluated the ethical part of the 30 projects selected by the Brittany Bienvenue Program.

- A. Krupa is a member of the CUMIR ("Commission des Utilisateurs des Moyens Informatiques pour la Recherche") of Centre Inria de l'Université de Rennes.

- E. Marchand is the head of "Robotics, Virtual Reality and Interaction" department at IRISA. Starting September 2022, he is the head of the Matisse Doctoral School.

- V. Drevelle is a member of the laboratory council of IRISA.

- M. Marchal is a member of the pedagogical council of EUR Digisport, a member of the scientific council of INSA Rennes, a member of the council of the Computer Science department at INSA Rennes, a member of the Council of the IRISA component of INSA Rennes.

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

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.

Alexandre Krupa:

- Master ESIR3: "Ultrasound visual servoing", 9 hours, M2, Esir Rennes
- Master INSA1: "Computer programming", 42 hours, L1, INSA Rennes

Eric Marchand:

- Master Esir2: "Colorimetry", 12 hours, M1, Esir Rennes
- Master Esir2: "Computer vision: geometry", 24 hours, M1, Esir Rennes
- Master Esir3: "Robotics Vision 1", 24 hours, M2, Esir Rennes
- Master Esir3: "Robotics Vision 2", 14 hours, M2, Esir Rennes
- Master MRI: "Computer vision", 12 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
- Licence ESIR 1: "System", 16h, L3, Université de Rennes 1

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
- Master INSA 1: "Probability", 14 hours, L3, INSA Rennes
- Master INSA: tutoring and support for students with disabilities, 30 hours, INSA Rennes

Claudio Pacchierotti:

- Master "Artificial Intelligence & Advanced Visual Computing": INF644 – Virtual/Augmented Reality & 3D Interactions", 6 hours, M2, École Polytechnique
- Master SIF: "Virtual Reality and Multi-Sensory Interaction", 4 hours, M2, IRISA.
- Master "Artificial Intelligence and Robotics"" "Medical robotics", 6 hours, University of Rome "La Sapienza

M. Marchal:

- Master INSA1: "Computer Graphics", 20 hours, M1, INSA Rennes.
- Master INSA1: "Complexity and algorithms", 26 hours, L3, INSA Rennes.
- Master INSA2: "Human-Computer Interaction", 15 hours, M2, INSA Rennes.
- Master INSA1: "Software design for medical applications", 6 hours, M1, INSA Rennes.

Vincent Drevelle:

- Master 2 ILA/CCNA: "Transverse project", 28 hours, M2, Université de Rennes 1

- Master 1 Info: "Artificial intelligence", 20 hours, M1, Université de Rennes 1

- Licence Info: "Computer systems architecture", 52 hours, L1, Université de Rennes 1

- Portail Info-Elec: "Discovering programming and electronics", 11 hours, L1, Université de Rennes 1

- Licence 3 Miage: "Computer programming", 78 hours, L3, Université de Rennes 1

- Master 2 EEEA-SE: "Instrumentation, localization, GPS", 4 hours, M2, Université de Rennes 1

- Master 2 EEEA-SE: "Multisensor data fusion", 20 hours, M2, Université de Rennes 1

- Master 2 IL/CCN: "Mobile robotics", 32 hours, M2, Université de Rennes 1

Julien Pettré:

- Master 2 SIF: "Motion for Animation and Robotics", 6 hours, Université de Rennes 1

- Master 2 Advanced 3D Graphics, "Crowd simulation", 3 hours, Ecole Polytechnique

Paolo Robuffo Giordano:

- Parcours Intelligence artificielle confirmés, SAFRAN, modules "Advanced Robotics", 12 heures

10.2.2   Supervision

- Ph.D. completed: Samuel Felton, "Deep Latent representations for visual servoing", defended in december 2022, supervised by Elisa Fromont and Eric Marchand.

- Ph.D. completed: Sebastian Vizcay, "Dexterous Interaction in Virtual Reality using High-Density Electrotactile Feedback," defended in December 2022, supervised by Maud Marchal, Ferran Argelaguet, and Claudio Pacchierotti.

- Ph.D. completed: Mathieu Gonzalez, "Optimzation of visual SLAM by Semantic Analysis of the environment", defended in November 2022, supervised by Eric Marchand.

- Ph.D. completed: Adèle Colas, "Modélisation de comportements collectifs réactifs et expressifs pour la réalité virtuelle" defended in November 2022, supervised by Julien Pettré, Ludovic Hoyet, Anne-Hélène Olivier, Claudio Pacchierotti.

- Ph.D. completed: Xi Wang "Improving robustness of monocular visual SLAM techniques: influence of contrasted local features, multi-planar representations and multimodal image analysis", defended in March 2022, supervised my Marc Christie and Eric Marchand

- Ph.D. completed: Alexander Oliva, "Integration of vision and force control for physical interaction with robotic manipulators" defended in February 2022, supervised by F. Chaumette and P. Robuffo Giordano [51]

- Ph.D. in progress: Pascal Brault, "Planification et optimisation de trajectoires robustes aux incer titudes paramétriques pour des taches robotiques fondées sur l'usage de capteurs", started in September 2019, supervised by Paolo Robuffo Giordano

- Ph.D. in progress: Emilie Leblong, "Taking into account social interactions in a virtual reality power wheelchair driving simulator: promoting learning for inclusive mobility", started in October 2020, supervised by Marie Babel and Anne-Hélène Olivier (Mimetic team)

- Ph.D. in progress: Ali Srour, "Robust and Control-Aware Motion Planning", started in October 2021, supervised by Paolo Robuffo Giordano and A. Franchi (Univ Twente, Netherlands)

- Ph.D. in progress: Nicola De Carli, "Reactive Trajectory Planning Methods for Formation Control and Localization of Multi-Robot System", started in January 2021, supervised by P. Salaris (Univ. Pisa, Italy) and Paolo Robuffo Giordano

- Ph.D. in progress: Lev Smolentsev, "Manipulation of soft bodies with multiple drones", started in November 2020, supervised by Alexandre Krupa, François Chaumette and Isabelle Fantoni (LS2N, Nantes)

- Ph.D. in progress: Fouad Makiyeh, "Shape servoing based on visual information using RGB-D sensor for dexterous manipulation of 3D compliant objects", started in September 2020, supervised by Alexandre Krupa, Maud Marchal and François Chaumette

- Ph.D. in progress: Maxime Robic, "Visual servoing of a satellite constellation", started in November 2020, supervised by Eric Marchand and François Chaumette.

- Ph.D. in progress: John Thomas, "Sensor-based control for assembly in congested area", started in December 2020, supervised by Francçois Chaumette.

- Ph.D. in progress: Thibault Noël, "Exploration of indoor environments", started in October 2021, supervised by Eric Marchand and François Chaumette.

- Ph.D. in progress: Mandela Ouafo Fonkoua,"Visual perception and visual servoing for dexterous robotic manipulation of compliant objects", started in October 2022, supervised by Alexandre Krupa and François Chaumette

- Ph.D. in progress: Antonio Marino, "Machine learning techniques for the control of multi-robot systems," started in September 2022, supervised by Paolo Robuffo Giordano and Claudio Pacchierotti.

- Ph.D. in progress: Lendy Mulot, "Design of coupling schemes for vibrotactile rendering in virtual reality," started in October 2022, supervised by Maud Marchal and Claudio Pacchierotti.

- Ph.D. in progress: Maxime Bernard, "Shared control for multi-robot systems," started in October 2021, supervised by Paolo Robuffo Giordano and Claudio Pacchierotti.

- Ph.D. in progress: Maxime Manzano, "Reach-to-grasp in activities of daily living: shared control of a multisensory assistive device to compensate for upper extremity neuromuscular disorders.", started in September 2022, supervised by Marie Babel and Sylvain Guégan

- Ph.D. in progress: Jose Eduardo Aguilar Segovia, "Design of haptic feedback using innovative shapeable materials", started in October 2022, supervised by Marie Babel, Sylvain Lefebvre (MFX team, Nancy) and Sylvain Guégan

- Ph.D. in progress: Oluwapelumi Williams, "Digital tools for accompaniment for sport for people with disabilities", started in December 2022, supervised by Marie Babel, Sylvain Guégan and Muriel Pressigout (IETR)

- Ph.D. in progress: Pierre-Antoine Cabaret, "Design of navigation techniques for a multisensory handle for mobility assistance," started in October 2021, supervised by Maud Marchal, Marie Babel, and Claudio Pacchierotti.

- Ph.D. in progress: Erwan Normand, "Augmenting the interaction with everyday objects with wearable haptics and Augmented Reality," started in October 2021, supervised by Eric Marchand, Maud Marchal, and Claudio Pacchierotti.

- Ph.D. in progress: Inès Lacôte, "Study of haptic and multisensory illusions to design a navigation assistance handle," started in January 2021, supervised by Maud Marchal, David Gueorguiev, and Claudio Pacchierotti.

- Ph.D. in progress: Glenn Kerbiriou, "Anatomical and Semantic Facial Modeling" started in May 2021, supervised by Maud Marchal and Quentin Avril.

- Ph.D. in progress: Lisheng Kuang, "Design and development of novel wearable haptic interfaces for teleoperation of robots," started in March 2020, supervised by Paolo Robuffo Giordano and Claudio Pacchierotti.

- 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 Julien Pettré, Ludovic Hoyet, Marc Christie, Claudio Pacchierotti.

10.2.3   Juries

PhD and HDR juries

- A. Krupa: Omid Aghajanzadeh (Ph.D., reviewer), Université Clermont Auvergne, France

- P. Robuffo Giordano: Marwan Johra (Ph.D, member), INSA Rennes; Martin Jacquet (Ph.D., reviewer), LAAS-CNRS, France; Guillaume Hardouin (Ph.D., president), ONERA, France; Luigi Penco (Ph.D., president), Inria Nancy Grand-Est, France

- F. Chaumette: Claudio Pacchierotti (HdR, president, IRISA), André Mateus (PhD, reviewer, IST Lisbon), Zheyu Zhuang (PhD, reviewer, ANU Canberra), Mathieu Gonzalez (PhD, president, IRT B-Com), Minttu Alakuijala (PhD, president, Inria Paris), Samuel Felton (PhD, president, IRISA)

- E. Marchand: Mathieu Zins (Ph.D., reviewer, Inria Lorraine), Ludovic Hoyet (HDR, President, Inria Rennes), Andrez Comport (HDR, I3S), Ludovic Burg (Ph.D., president, IRISA).

- M. Marchal: Mehdi Boudissa (HDR, reviewer) Univ. Grenoble Alpes, Paul Baksic (Ph.D., reviewer), Univ. Strasbourg, David Jourdan (Ph.D., reviewer), Univ. Côte d'Azur, Felix Vanneste (Ph.D., president), Univ. Lille.

- M. Babel: Phani-Teja Singamaneni (PhD, reviewer, Univ. Toulouse), Lorenzo Vianello (PhD, reviewer, Univ. Lorraine Nancy), Jessica Colombel (PhD, reviewer, Univ. Lorraine Nancy), Songming Chen (PhD, president, Ecole Centrale Nantes)

10.3   Popularization

10.3.1   Interventions

- C. Pacchierotti. "Haptique: la science du toucher." Presentation to the Association des journalistes scientifiques de la presse d'information (AJSPI), online, 2022.

- Maxime Robic has been awarded as the winner of the 3rd jury price of "Ma thése en 180 secondes" during the national final in Lyon in May 2022.

10.3.2   Articles and contents

- M. Marchal. "Femmes de sciences". Radio France Internationale, February 2022; "Parce que, parfois, l'essentiel est invisible", Travail et sécurité, March 2022; "La réalité virtuelle entre dans l'ère du tactile", Les Echos, May 2022; "Une réalité virtuelle encore plus tactile", Inside Labs, October 2022.

11   Scientific production

11.1   Major publications

[1]   M. Aggravi, C. Pacchierotti and P. Robuffo Giordano. 'Connectivity-Maintenance Teleoperation of a UAV Fleet with Wearable Haptic Feedback'. In: *IEEE Transactions on Automation Science and Engineering* (June 2020), pp. 1–20. DOI: 10.1109/TASE.2020.3000060. URL: https://hal.inria.fr/hal-02866459.

[2]   J. Chevrie, A. Krupa and 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, 20th May 2019, pp. 1–7. URL: https://hal.inria.fr/hal-02053101.

[3]   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 and P. Rabate. 'Humanoid robots in aircraft manufacturing'. In: *IEEE Robotics and Automation Magazine* 26.4 (Dec. 2019), pp. 30–45. DOI: 10.1109/MRA.2019.2943395. URL: https://hal-lirmm.ccsd.cnrs.fr/lirmm-02303117.

[4]   R. Lagneau, A. Krupa and M. Marchal. 'Automatic Shape Control of Deformable Wires based on Model-Free Visual Servoing'. In: *IEEE Robotics and Automation Letters* 5.4 (2020), pp. 5252–5259. DOI: 10.1109/LRA.2020.3007114. URL: https://hal.inria.fr/hal-02890830.

[5]   B. Pascual-Escudero, A. Nayak, S. Briot, O. Kermorgant, P. Martinet, M. Safey El Din and F. Chaumette. 'Complete Singularity Analysis for the Perspective-Four-Point Problem'. In: *International Journal of Computer Vision* 129.4 (Apr. 2021), pp. 1217–1237. DOI: 10.1007/s11263-020-01420-0. URL: https://hal.archives-ouvertes.fr/hal-03070525.

[6]   B. Penin, P. Robuffo Giordano and F. Chaumette. 'Vision-Based Reactive Planning for Aggressive Target Tracking while Avoiding Collisions and Occlusions'. In: *IEEE Robotics and Automation Letters* 3.4 (Oct. 2018), pp. 3725–3732. DOI: 10.1109/LRA.2018.2856526. URL: https://hal.inria.fr/hal-01836586.

[7]   P. Salaris, M. Cognetti, R. Spica and P. Robuffo Giordano. 'Online Optimal Perception-Aware Trajectory Generation'. In: *IEEE Transactions on Robotics* (2019), pp. 1–16. DOI: 10.1109/TRO.2019.2931137. URL: https://hal.inria.fr/hal-02278900.

[8]   M. Selvaggio, J. Cacace, C. Pacchierotti, F. Ruggiero and P. Robuffo Giordano. 'A Shared-control Teleoperation Architecture for Nonprehensile Object Transportation'. In: *IEEE Transactions on Robotics* (June 2021), pp. 1–15. DOI: 10.1109/TRO.2021.3086773. URL: https://hal.inria.fr/hal-03246629.

[9]   A. Sengupta, R. Lagneau, A. Krupa, E. Marchand and M. Marchal. 'Simultaneous Tracking and Elasticity Parameter Estimation of Deformable Objects'. In: ICRA 2020 - IEEE International Conference on Robotics and Automation. Paris, France: IEEE, 31st May 2020, pp. 1–7. URL: https://hal.inria.fr/hal-02495831.

11.2   Publications of the year

International journals

[10]   M. Aggravi, G. Sirignano, P. Robuffo Giordano and C. Pacchierotti. 'Decentralized control of a heterogeneous human-robot team for exploration and patrolling'. In: *IEEE Transactions on Automation Science and Engineering* 19.4 (Sept. 2022), pp. 3109–3125. DOI: 10.1109/TASE.2021.3106386. URL: https://hal.inria.fr/hal-03321834.

[11]   G. Barresi, C. Pacchierotti, M. Laffranchi and L. de Michieli. 'Beyond Digital Twins: Phygital Twins for Neuroergonomics in Human-Robot Interaction'. In: *Frontiers in Neurorobotics* 16 (28th June 2022). DOI: 10.3389/fnbot.2022.913605. URL: https://hal.inria.fr/hal-03706810.

[12]   A. Bernardin, E. Coevoet, P. Kry, S. Andrews, C. Duriez and M. Marchal. 'Constraint-based Simulation of Passive Suction Cups'. In: *ACM Transactions on Graphics* 42.1 (28th Feb. 2023), pp. 1–14. DOI: 10.1145/3551889. URL: https://hal.inria.fr/hal-03869711.

[13]   F. Berton, F. Grzeskowiak, A. Bonneau, A. Jovane, M. Aggravi, L. Hoyet, A.-H. Olivier, C. Pacchierotti and J. Pettré. 'Crowd Navigation in VR: exploring haptic rendering of collisions'. In: *IEEE Transactions on Visualization and Computer Graphics* 28.7 (1st July 2022), pp. 2589–2601. DOI: 10.1109/TVCG.2020.3041341. URL: https://hal.inria.fr/hal-03038344.

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[15]   S. Felton, P. Brault, E. Fromont and E. Marchand. 'Visual Servoing in Autoencoder Latent Space'. In: *IEEE Robotics and Automation Letters* 7.2 (Apr. 2022), pp. 3234–3241. DOI: 10.1109/LRA.2022.3144490. URL: https://hal.inria.fr/hal-03506036.

[16]   M. Gonzalez, E. Marchand, A. Kacete and J. Royan. 'TwistSLAM: Constrained SLAM in Dynamic Environment'. In: *IEEE Robotics and Automation Letters* 7.3 (July 2022), pp. 6846–6853. URL: https://hal.inria.fr/hal-03676527.

[17]   T. Howard, K. K. Driller, W. Frier, C. Pacchierotti, M. Marchal and J. Hartcher-O'Brien. 'Gap detection in pairs of ultrasound mid-air vibrotactile stimuli'. In: *ACM Transactions on Applied Perception* (Nov. 2022), pp. 1–18. DOI: 10.1145/3570904. URL: https://hal.inria.fr/hal-03838682.

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[20]   P. Kourtesis, S. Vizcay, M. Marchal, C. Pacchierotti and F. Argelaguet. 'Action-Specific Perception & Performance on a Fitts's Law Task in Virtual Reality: The Role of Haptic Feedback'. In: *IEEE Transactions on Visualization and Computer Graphics* (2022), pp. 1–12. DOI: 10.1109/TVCG.2022.3203003. URL: https://hal.inria.fr/hal-03770458.

[21]   F. Morbidi, L. Devigne, C. S. Teodorescu, B. Fraudet, E. Leblong, T. Carlson, M. Babel, G. Caron, S. Delmas, F. Pasteau, G. Vailland, V. Gouranton, S. Guegan, R. Le Breton and N. Ragot. 'Assistive Robotic Technologies for Next-Generation Smart Wheelchairs: Codesign and Modularity to Improve Users' Quality of Life'. In: *IEEE Robotics and Automation Magazine* (June 2022), pp. 2–14. DOI: 10.1109/MRA.2022.3178965. URL: https://hal.archives-ouvertes.fr/hal-03709574.

[22]   X. Wang, M. Christie and E. Marchand. 'Binary Graph Descriptor for Robust Relocalization on Heterogeneous Data'. In: *IEEE Robotics and Automation Letters* 7.2 (2022), pp. 2008–2015. DOI: 10.1109/LRA.2022.3142854. URL: https://hal.inria.fr/hal-03506034.

International peer-reviewed conferences

[23]   C. Böhm, P. Brault, Q. Delamare, P. Giordano and S. Weiss. 'COP: Control & Observability-aware Planning'. In: ICRA 2022 - IEEE International Conference on Robotics and Automation. Philadelphia, United States, 23rd May 2022, pp. 3364–3370. DOI: 10.1109/ICRA46639.2022.9812373. URL: https://hal.inria.fr/hal-03654316.

[24]   E. Bouzbib and G. Bailly. '"Let's Meet and Work it Out": Understanding and Mitigating Encountered-Type of Haptic Devices Failure Modes in VR'. In: VR 2022 - IEEE Conference on Virtual Reality. Christchurch, New Zealand: IEEE, 12th Mar. 2022. URL: https://hal.science/hal-03548113.

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[26]   R. Fernandez-Fernandez, M. Aggravi, P. R. Giordano, J. G. Victores and C. Pacchierotti. 'Neural Style Transfer with Twin-Delayed DDPG for Shared Control of Robotic Manipulators'. In: ICRA 2022 - 39th IEEE International Conference on Robotics and Automation. Philadelphia, United States, 23rd May 2022, pp. 4073–4079. DOI: 10.1109/ICRA46639.2022.9812245. URL: https://hal.inria.fr/hal-03584085.

[27]   M. Gonzalez, E. Marchand, A. Kacete and J. Royan. 'S3LAM: Structured Scene SLAM'. In: IROS 2022 - IEEE/RSJ International Conference on Intelligent Robots and Systems. Kyoto, Japan: IEEE, 23rd Oct. 2022, pp. 1–7. URL: https://hal.inria.fr/hal-03718328.

[28] F. Grzeskowiak, L. Devigne, F. Pasteau, G. Souza Vieira Dutra, M. Babel and S. Guégan. 'SWALKIT: A generic augmented walker kit to provide haptic feedback navigation assistance to people with both visual and motor impairments'. In: IEEE Int. Conf. on Rehabilitation Robotics, ICORR'22. Rotterdam, Netherlands: IEEE, July 2022, pp. 1–6. URL: https://hal.science/hal-03709659.

[29] E. Hummel, C. Pacchierotti, V. Gouranton, R. Gaugne, T. Nicolas and A. Lécuyer. 'Haptic Rattle: Multi-Modal Rendering of Virtual Objects Inside a Hollow Container'. In: EuroHaptics 2022 - International conference on Haptics: Science, Technology, Applications. Hamburg, Germany, 22nd May 2022, pp. 1–8. DOI: 10.1007/978-3-031-06249-0_22. URL: https://hal.inria.fr/hal-03614072.

[30] L. Kuang, M. Aggravi, P. R. Giordano and C. Pacchierotti. 'Wearable cutaneous device for applying position/location haptic feedback in navigation applications'. In: HAPTICS 2022 - IEEE Haptics Symposium. Santa Barbara, United States: IEEE, 21st Mar. 2022, pp. 1–6. DOI: 10.1109/HAPTICS52432.2022.9765619. URL: https://hal.inria.fr/hal-03551814.

[31] L. Kuang, M. Marchal, M. Aggravi, P. Robuffo Giordano and C. Pacchierotti. 'Design of a 2-DoF Haptic Device for Motion Guidance'. In: EuroHaptics 2022 - International conference on Haptics: Science, Technology, Applications. Hamburg, Germany, 22nd May 2022, pp. 1–8. URL: https://hal.inria.fr/hal-03614070.

[32] L. Kuang, M. Marchal, P. Robuffo Giordano and C. Pacchierotti. 'Rolling Handle for Hand Motion Guidance and Teleoperation'. In: EuroHaptics 2022 - International Conference on Haptics: Science, Technology, Applications. Hamburg, Germany, 22nd May 2022, pp. 1–3. URL: https://hal.inria.fr/hal-03624750.

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[34] I. Lacôte, C. Pacchierotti, M. Babel, M. Marchal and D. Gueorguiev. '"Tap Stimulation": An Alternative To Vibrations To Convey The Apparent Haptic Motion Illusion'. In: HAPTICS 2022 - IEEE Haptics Symposium. Santa Barbara, United States, 21st Mar. 2022. URL: https://hal.inria.fr/hal-03551830.

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[36] T. Noël, S. Kabbour, A. Lehuger, E. Marchand and F. Chaumette. 'Disk-Graph Probabilistic Roadmap: Biased Distance Sampling for Path Planning in a Partially Unknown Environment'. In: IROS 2022 – IEEE/RSJ International Conference on Intelligent Robots and Systems. Kyoto, Japan, 23rd Oct. 2022, pp. 1–8. URL: https://hal.inria.fr/hal-03752195.

[37] G. Notomista, C. Pacchierotti and P. Robuffo Giordano. 'Multi-robot persistent environmental monitoring based on constraint-driven execution of learned robot tasks'. In: ICRA 2022 - IEEE International Conference on Robotics and Automation. Philadelphia, United States: IEEE, 23rd May 2022, pp. 6853–6859. DOI: 10.1109/ICRA46639.2022.9811673. URL: https://hal.inria.fr/hal-03594774.

[38] A. Oliva, E. Aertbeliën, J. de Schutter, P. Robuffo Giordano and F. Chaumette. 'Towards Dynamic Visual Servoing for Interaction Control and Moving Targets'. In: ICRA 2022 - IEEE International Conference on Robotics and Automation. Philadelphia, United States, 23rd May 2022, pp. 150–156. URL: https://hal.inria.fr/hal-03654156.

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[41]   M. Robic, R. Fraisse, K. Lagadec, E. Marchand and F. Chaumette. 'Visual servoing of an Earth observation satellite of the LION constellation'. In: IAC 2022 - 73rd International Astronautical Congress. Paris, France, 18th Sept. 2022, pp. 1–9. URL: https://hal.inria.fr/hal-03768194.

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[46]   M. Gonzalez, E. Marchand, A. Kacete and J. Royan. 'S3LAM: SLAM à Scène Structurée'. In: GRETSI 2022 - XXVIIIème Colloque Francophone de Traitement du Signal et des Images. Nancy, France, 6th Sept. 2022, pp. 1–4. URL: https://hal.inria.fr/hal-03711725.

Conferences without proceedings

[47]   E. Leblong, P. Piette, M. Dandois, E. Ceze, L. Devigne, F. Pasteau, M. Babel, B. Fraudet, B. J. Mcfadyen and A.-H. Olivier. 'Navigation dans les musées de la ville de Rennes : approche écologique pour l'évaluation d'un module d'assistance à la conduite lors des interactions des usagers de fauteuil roulant électrique dans un environnement complexe.' In: SOFPEL 2022 - 28ème congrès de la Société Francophone Posture Équilibre et Locomotion. Marseille, France, 1st Dec. 2022. URL: https://hal.inria.fr/hal-03921410.

[48]   E. Leblong, P. Piette, M. Dandois, E. Ceze, L. Devigne, F. Pasteau, M. Babel and A.-H. Olivier. 'Evaluation de la confiance en soi lors de la visite d'un musée grâce à un module d'assistance à la conduite de fauteuil roulant électrique : Etude observationnelle prospective dans les musées de la ville de Rennes'. In: SOFPEL 2022 - 28ème congrès de la Société Francophone Posture Équilibre et Locomotion. Rennes, France, 1st Dec. 2022. URL: https://hal.inria.fr/hal-03921378.

Scientific book chapters

[49]   O. Georgiou, W. Frier, E. Freeman, C. Pacchierotti and T. Hoshi. 'Mid-Air Haptics: Future Challenges and Opportunities'. In: *Ultrasound Mid-Air Haptics for Touchless Interfaces*. Human–Computer Interaction Series. Springer International Publishing, 17th Sept. 2022, pp. 385–397. DOI: 10.1007 /978-3-031-04043-6_18. URL: https://hal.inria.fr/hal-03781035.

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Doctoral dissertations and habilitation theses

[51] A. Oliva. 'Integration of vision and force control for physical interaction with robotic manipulators'. Université Rennes 1, 22nd Feb. 2022. URL: https://theses.hal.science/tel-03690426.

[52] C. Pacchierotti. 'Cutaneous haptic feedback for robotics and Virtual Reality'. Université de Rennes 1 (UR1), Rennes, FRA., 4th Feb. 2022. URL: https://theses.hal.science/tel-03576321.

Other scientific publications

[53] F. Chinello, C. Pacchierotti, C. Fang and H. Seifi. *Tutorial in "Frontiers in Haptic Technology and Interaction Design: the Challenges, the Technology, the Perspectives"*. Aarhus, Denmark, 8th Oct. 2022. DOI: 10.1145/3547522.3558898. URL: https://hal.inria.fr/hal-03807745.

[54] A.-H. Olivier, M. Babel, A. Crétual, L. Nicolas, L. Devigne, F. Pasteau, B. Fraudet, E. Leblong and J. Pettré. 'Comment rejoindre un groupe quand on se déplace en fauteuil ? Etude observationnelle biomécanique des interactions piétons-usagers de fauteuil roulant'. In: SOFMER 2022 - 37e congrès de la Société Française de Médecine Physique et de Réadaptation. Rennes, France, 1st Dec. 2022. URL: https://hal.inria.fr/hal-03921399.

11.3   Cited publications

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