UMR IRISA

Activity Report 2019

Team HYBRID

3D Interaction with Virtual Environments using Body and Mind

Joint team with Inria Rennes – Bretagne Atlantique

D6 – Media and Interactions

Table of contents

Project-Team HYBRID

Creation of the Team: 2013 January 01, updated into Project-Team: 2013 July 01

Keywords:

Computer Science and Digital Science:

A2.5. - Software engineering
A5. - Interaction, multimedia and robotics
A5.1. - Human-Computer Interaction
A5.1.1. - Engineering of interactive systems
A5.1.2. - Evaluation of interactive systems
A5.1.3. - Haptic interfaces
A5.1.4. - Brain-computer interfaces, physiological computing
A5.1.5. - Body-based interfaces
A5.1.6. - Tangible interfaces
A5.1.7. - Multimodal interfaces
A5.1.8. - 3D User Interfaces
A5.1.9. - User and perceptual studies
A5.5.4. - Animation
A5.6. - Virtual reality, augmented reality
A5.6.1. - Virtual reality
A5.6.2. - Augmented reality
A5.6.3. - Avatar simulation and embodiment
A5.6.4. - Multisensory feedback and interfaces
A5.10.5. - Robot interaction (with the environment, humans, other robots)
A6. - Modeling, simulation and control
A6.2. - Scientific computing, Numerical Analysis & Optimization
A6.3. - Computation-data interaction

Other Research Topics and Application Domains:

B1.2. - Neuroscience and cognitive science
B2. - Health
B2.4. - Therapies
B2.5. - Handicap and personal assistances
B2.6. - Biological and medical imaging
B2.7. - Medical devices
B2.7.1. - Surgical devices
B2.8. - Sports, performance, motor skills
B5. - Industry of the future
B5.1. - Factory of the future
B5.2. - Design and manufacturing
B5.6. - Robotic systems
B5.8. - Learning and training
B5.9. - Industrial maintenance

B6.4. - Internet of things
B8.1. - Smart building/home
B8.3. - Urbanism and urban planning
B9.1. - Education
B9.2. - Art
B9.2.2. - Cinema, Television
B9.2.3. - Video games
B9.4. - Sports
B9.6.6. - Archeology, History

1. Team, Visitors, External Collaborators

Research Scientists

Anatole Lécuyer [Team leader, Inria, Senior Researcher, HDR]
Ferran Argelaguet [Inria, Researcher]

Faculty Members

Bruno Arnaldi [INSA Rennes, Professor, HDR]
Valérie Gouranton [INSA Rennes, Associate Professor]
Maud Marchal [INSA Rennes, Associate Professor, HDR]

Post-Doctoral Fellows

Giulia Lioi [Inria]
Thomas Howard [Inria]

PhD Students

Hakim Si Mohammed [Inria, until Dec 2019]
Guillaume Bataille [Orange Labs]
Antonin Bernardin [INSA Rennes]
Xavier de Tinguy de La Girouliere [ENS Paris]
Rebecca Fribourg [Inria]
Romain Lagneau [INSA Rennes]
Flavien Lécuyer [INSA Rennes]
Tiffany Luong [IRT B<>com]
Etienne Peillard [Inria]
Romain Terrier [IRT B<>com]
Mathis Fleury [Inria]
Guillaume Vailland [INSA Rennes]
Hugo Brument [Univ de Rennes I]
Diane Dewez [Inria]
Gerard Gallagher [Inria, until Nov 2019]
Victor Rodrigo Mercado Garcia [Inria]
Nicolas Olivier [InterDigital, from Feb 2019]
Gwendal Fouché [Inria, from Oct 2019]
Grégoire Richard [Inria, from Oct 2019]
Sebastian Vizcay [Inria, from Nov 2019]
Martin Guy [ECN, from Oct 2019]
Adelaide Genay [Inria, from Oct 2019]

Technical staff

Hakim Si Mohammed [Inria, Engineer, from Dec 2019]
Alexandre Audinot [INSA Rennes, Engineer]

Adrien Reuzeau [INSA Rennes, Engineer]
Thierry Gaugry [INSA Rennes, Engineer]
Florian Nouviale [INSA Rennes, Research Engineer]
Ronan Gaugne [Université de Rennes 1, Research Engineer]
Kevin-Yoren Gaffary [INSA Rennes, Engineer, until Sep 2019]
Emeric Goga [SATT Ouest Valorisation, Engineer, until Mar 2019]
Carl-Johan Jorgensen [SATT Ouest Valorisation, Engineer, until Mar 2019]
Vincent Goupil [SATT Ouest Valorisation, Engineer, until Mar 2019]
Quentin Petit [INSA Rennes, Engineer, until Jul 2019]

Administrative Assistant

Nathalie Denis [Inria]

External Collaborators

Guillaume Moreau [Ecole Centrale de Nantes]
Jean-Marie Normand [Ecole Centrale de Nantes]
Mélanie Cogné [PhD, CHU Rennes]

2. Overall Objectives

2.1. Overall Objectives

Our research project belongs to the scientific field of Virtual Reality (VR) and 3D interaction with virtual environments. VR systems can be used in numerous applications such as for industry (virtual prototyping, assembly or maintenance operations, data visualization), entertainment (video games, theme parks), arts and design (interactive sketching or sculpture, CAD, architectural mock-ups), education and science (physical simulations, virtual classrooms), or medicine (surgical training, rehabilitation systems). A major change that we foresee in the next decade concerning the field of Virtual Reality relates to the emergence of new paradigms of interaction (input/output) with Virtual Environments (VE).

As for today, the most common way to interact with 3D content still remains by measuring user's motor activity, i.e., his/her gestures and physical motions when manipulating different kinds of input device. However, a recent trend consists in soliciting more movements and more physical engagement of the body of the user. We can notably stress the emergence of bimanual interaction, natural walking interfaces, and whole-body involvement. These new interaction schemes bring a new level of complexity in terms of generic physical simulation of potential interactions between the virtual body and the virtual surrounding, and a challenging "trade-off" between performance and realism. Moreover, research is also needed to characterize the influence of these new sensory cues on the resulting feelings of "presence" and immersion of the user.

Besides, a novel kind of user input has recently appeared in the field of virtual reality: the user's mental activity, which can be measured by means of a "Brain-Computer Interface" (BCI). Brain-Computer Interfaces are communication systems which measure user's electrical cerebral activity and translate it, in real-time, into an exploitable command. BCIs introduce a new way of interacting "by thought" with virtual environments. However, current BCI can only extract a small amount of mental states and hence a small number of mental commands. Thus, research is still needed here to extend the capacities of BCI, and to better exploit the few available mental states in virtual environments.

Our first motivation consists thus in designing novel "body-based" and "mind-based" controls of virtual environments and reaching, in both cases, more immersive and more efficient 3D interaction.

Furthermore, in current VR systems, motor activities and mental activities are always considered separately and exclusively. This reminds the well-known “body-mind dualism” which is at the heart of historical philosophical debates. In this context, our objective is to introduce novel “hybrid” interaction schemes in virtual reality, by considering motor and mental activities jointly, i.e., in a harmonious, complementary, and optimized way. Thus, we intend to explore novel paradigms of 3D interaction mixing body and mind inputs. Moreover, our approach becomes even more challenging when considering and connecting multiple users which implies multiple bodies and multiple brains collaborating and interacting in virtual reality.

Our second motivation consists thus in introducing a “hybrid approach” which will mix mental and motor activities of one or multiple users in virtual reality.

3. Research Program

3.1. Research Program

The scientific objective of Hybrid team is to improve 3D interaction of one or multiple users with virtual environments, by making full use of physical engagement of the body, and by incorporating the mental states by means of brain-computer interfaces. We intend to improve each component of this framework individually, but we also want to improve the subsequent combinations of these components.

The "hybrid" 3D interaction loop between one or multiple users and a virtual environment is depicted in Figure 1. Different kinds of 3D interaction situations are distinguished (red arrows, bottom): 1) body-based interaction, 2) mind-based interaction, 3) hybrid and/or 4) collaborative interaction (with at least two users). In each case, three scientific challenges arise which correspond to the three successive steps of the 3D interaction loop (blue squares, top): 1) the 3D interaction technique, 2) the modeling and simulation of the 3D scenario, and 3) the design of appropriate sensory feedback.

The 3D interaction loop involves various possible inputs from the user(s) and different kinds of output (or sensory feedback) from the simulated environment. Each user can involve his/her body and mind by means of corporal and/or brain-computer interfaces. A hybrid 3D interaction technique (1) mixes mental and motor inputs and translates them into a command for the virtual environment. The real-time simulation (2) of the virtual environment is taking into account these commands to change and update the state of the virtual world and virtual objects. The state changes are sent back to the user and perceived by means of different sensory feedbacks (e.g., visual, haptic and/or auditory) (3). The sensory feedbacks are closing the 3D interaction loop. Other users can also interact with the virtual environment using the same procedure, and can eventually “collaborate” by means of “collaborative interactive techniques” (4).

This description is stressing three major challenges which correspond to three mandatory steps when designing 3D interaction with virtual environments:

- **3D interaction techniques:** This first step consists in translating the actions or intentions of the user (inputs) into an explicit command for the virtual environment. In virtual reality, the classical tasks that require such kinds of user command were early categorized in four [44]: navigating the virtual world, selecting a virtual object, manipulating it, or controlling the application (entering text, activating options, etc). The addition of a third dimension, the use of stereoscopic rendering and the use of advanced VR interfaces make however inappropriate many techniques that proved efficient in 2D, and make it necessary to design specific interaction techniques and adapted tools. This challenge is here renewed by the various kinds of 3D interaction which are targeted. In our case, we consider various cases, with motor and/or cerebral inputs, and potentially multiple users.
- **Modeling and simulation of complex 3D scenarios:** This second step corresponds to the update of the state of the virtual environment, in real-time, in response to all the potential commands or actions sent by the user. The complexity of the data and phenomena involved in 3D scenarios is constantly increasing. It corresponds for instance to the multiple states of the entities present in the simulation (rigid, articulated, deformable, fluids, which can constitute both the user’s virtual body

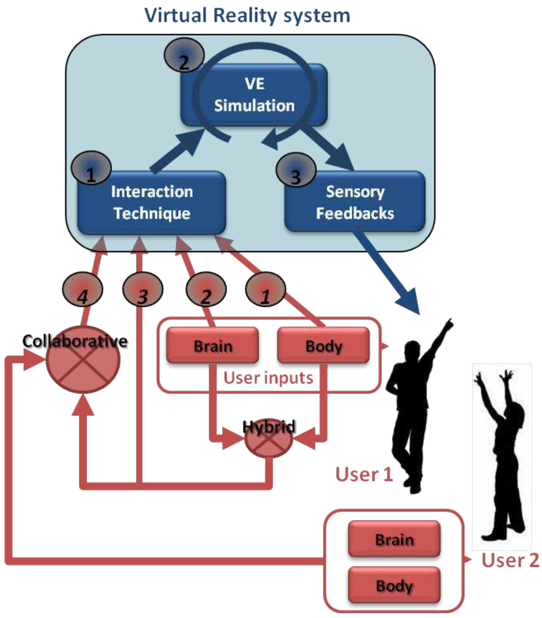

Figure 1. 3D hybrid interaction loop between one or multiple users and a virtual reality system. Top (in blue) three steps of 3D interaction with a virtual environment: (1-blue) interaction technique, (2-blue) simulation of the virtual environment, (3-blue) sensory feedbacks. Bottom (in red) different cases of interaction: (1-red) body-based, (2-red) mind-based, (3-red) hybrid, and (4-red) collaborative 3D interaction.

and the different manipulated objects), and the multiple physical phenomena implied by natural human interactions (squeezing, breaking, melting, etc). The challenge consists here in modeling and simulating these complex 3D scenarios and meeting, at the same time, two strong constraints of virtual reality systems: performance (real-time and interactivity) and genericity (e.g., multi-resolution, multi-modal, multi-platform, etc).

- **Immersive sensory feedbacks:** This third step corresponds to the display of the multiple sensory feedbacks (output) coming from the various VR interfaces. These feedbacks enable the user to perceive the changes occurring in the virtual environment. They are closing the 3D interaction loop, making the user immersed, and potentially generating a subsequent feeling of presence. Among the various VR interfaces which have been developed so far we can stress two kinds of sensory feedback: visual feedback (3D stereoscopic images using projection-based systems such as CAVE systems or Head Mounted Displays); and haptic feedback (related to the sense of touch and to tactile or force-feedback devices). The Hybrid team has a strong expertize in haptic feedback, and in the design of haptic and “pseudo-haptic” rendering [45]. Note that a major trend in the community, which is strongly supported by the Hybrid team, relates to a “perception-based” approach, which aims at designing sensory feedbacks which are well in line with human perceptual capacities.

These three scientific challenges are addressed differently according to the context and the user inputs involved. We propose to consider three different contexts, which correspond to the three different research axes of the Hybrid research team, namely: 1) body-based interaction (motor input only), 2) mind-based interaction (cerebral input only), and then 3) hybrid and collaborative interaction (i.e., the mixing of body and brain inputs from one or multiple users).

3.2. Research Axes

The scientific activity of Hybrid team follows three main axes of research:

- **Body-based interaction in virtual reality.** Our first research axis concerns the design of immersive and effective "body-based" 3D interactions, i.e., relying on a physical engagement of the user’s body. This trend is probably the most popular one in VR research at the moment. Most VR setups make use of tracking systems which measure specific positions or actions of the user in order to interact with a virtual environment. However, in recent years, novel options have emerged for measuring “full-body” movements or other, even less conventional, inputs (e.g. body equilibrium). In this first research axis we are thus concerned by the emergence of new kinds of “body-based interaction” with virtual environments. This implies the design of novel 3D user interfaces and novel 3D interactive techniques, novel simulation models and techniques, and novel sensory feedbacks for body-based interaction with virtual worlds. It involves real-time physical simulation of complex interactive phenomena, and the design of corresponding haptic and pseudo-haptic feedback.
- **Mind-based interaction in virtual reality.** Our second research axis concerns the design of immersive and effective “mind-based” 3D interactions in Virtual Reality. Mind-based interaction with virtual environments is making use of Brain-Computer Interface technology. This technology corresponds to the direct use of brain signals to send “mental commands” to an automated system such as a robot, a prosthesis, or a virtual environment. BCI is a rapidly growing area of research and several impressive prototypes are already available. However, the emergence of such a novel user input is also calling for novel and dedicated 3D user interfaces. This implies to study the extension of the mental vocabulary available for 3D interaction with VE, then the design of specific 3D interaction techniques "driven by the mind" and, last, the design of immersive sensory feedbacks that could help improving the learning of brain control in VR.
- **Hybrid and collaborative 3D interaction.** Our third research axis intends to study the combination of motor and mental inputs in VR, for one or multiple users. This concerns the design of mixed systems, with potentially collaborative scenarios involving multiple users, and thus, multiple bodies and multiple brains sharing the same VE. This research axis therefore involves two interdependent topics: 1) collaborative virtual environments, and 2) hybrid interaction. It should end up with

collaborative virtual environments with multiple users, and shared systems with body and mind inputs.

4. Application Domains

4.1. Overview

The research program of Hybrid team aims at next generations of virtual reality and 3D user interfaces which could possibly address both the “body” and “mind” of the user. Novel interaction schemes are designed, for one or multiple users. We target better integrated systems and more compelling user experiences.

The applications of our research program correspond to the applications of virtual reality technologies which could benefit from the addition of novel body-based or mind-based interaction capabilities:

- **Industry**: with training systems, virtual prototyping, or scientific visualization;
- **Medicine**: with rehabilitation and reeducation systems, or surgical training simulators;
- **Entertainment**: with movie industry, content customization, video games or attractions in theme parks,
- **Construction**: with virtual mock-ups design and review, or historical/architectural visits.
- **Cultural Heritage**: with acquisition, virtual excavation, virtual reconstruction and visualization

5. Highlights of the Year

5.1. Highlights of the Year

- Mélanie Cogné (Medical Doctor, PhD, CHU Rennes) has joined the Hybrid team as a new External Collaborator.
- Hybrid team has been strongly involved in the organization of the IEEE Virtual Reality Conference 2019 (IEEE VR), with F. Argelaguet (Program Chair) and A. Lécuyer (Panels Chair) and Jean-Marie Normand (Program Committee).
- The Immersia VR platform has celebrated its 20 years of existence at Inria Rennes/IRISA center, within the “20ans d’Immersia” event (November 2019).
- Hybrid team has organized a “VR Hackathon” at the Inria Rennes/IRISA Center, gathering around 20 participants (May 2019).

5.1.1. Awards

- IEEE VGTC Virtual Reality Technical Achievement Award 2019 was obtained by Anatole Lécuyer.
- IEEE VR Best 3DUI Contest Demo Award 2019: was obtained by Team Hybrid (Hugo Brument, Rebecca Fribourg, Gerard Gallagher, Thomas Howard, Flavien Lecuyer, Tiffany Luong, Victor Mercado, Etienne Peillard, Xavier de Tinguy, and Maud Marchal), for the demo entitled “Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario” [11].

BEST PAPERS AWARDS:

[31]
E. PEILLARD, T. THEBAUD, J.-M. NORMAND, F. ARGELAGUET SANZ, G. MOREAU, A. LÉCUYER. *Virtual Objects Look Farther on the Sides: The Anisotropy of Distance Perception in Virtual Reality*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, March 2019, pp. 227-236 [*DOI :* 10.1109/VR.2019.8797826], https://hal.archives-ouvertes.fr/hal-02084069

[18]

R. GAUGNE, T. NICOLAS, Q. PETIT, M. OTSUKI, V. GOURANTON. *Evaluation of a Mixed Reality based Method for Archaeological Excavation Support*, in "ICAT-EGVE 2019 - International Conference on Artificial Reality and Telexistence - Eurographics Symposium on Virtual Environments", Tokyo, Japan, September 2019, pp. 1-8, https://hal.inria.fr/hal-02272910

[23]
J. LACOCHE, T. DUVAL, B. ARNALDI, E. MAISEL, J. ROYAN. *Machine Learning Based Interaction Technique Selection For 3D User Interfaces*, in "EuroVR 2019 - 16th EuroVR International Conference", Tallinn, Estonia, Springer, October 2019, pp. 33-51 [*DOI :* 10.1007/978-3-030-31908-3_3], https://hal.archives-ouvertes.fr/hal-02292434

6. New Software and Platforms

6.1. #FIVE

Framework for Interactive Virtual Environments

KEYWORDS: Virtual reality - 3D - 3D interaction - Behavior modeling

SCIENTIFIC DESCRIPTION: #FIVE (Framework for Interactive Virtual Environments) is a framework for the development of interactive and collaborative virtual environments. #FIVE was developed to answer the need for an easier and a faster design and development of virtual reality applications. #FIVE provides a toolkit that simplifies the declaration of possible actions and behaviours of objects in a VE. It also provides a toolkit that facilitates the setting and the management of collaborative interactions in a VE. It is compliant with a distribution of the VE on different setups. It also proposes guidelines to efficiently create a collaborative and interactive VE. The current implementation is in C# and comes with a Unity3D engine integration, compatible with MiddleVR framework.

FUNCTIONAL DESCRIPTION: #FIVE contains software modules that can be interconnected and helps in building interactive and collaborative virtual environments. The user can focus on domain-specific aspects for his/her application (industrial training, medical training, etc) thanks to #FIVE's modules. These modules can be used in a vast range of domains using virtual reality applications and requiring interactive environments and collaboration, such as in training for example.

- Participants: Florian Nouviale, Valérie Gouranton, Bruno Arnaldi, Vincent Goupil, Carl-Johan Jorgensen, Emeric Goga, Adrien Reuzeau and Alexandre Audinot
- Contact: Valérie Gouranton
- Publication: #FIVE : High-Level Components for Developing Collaborative and Interactive Virtual Environments
- URL: https://bil.inria.fr/fr/software/view/2527/tab

6.2. #SEVEN

Sensor Effector Based Scenarios Model for Driving Collaborative Virtual Environments

KEYWORDS: Virtual reality - Interactive Scenarios - 3D interaction

SCIENTIFIC DESCRIPTION: #SEVEN (Sensor Effector Based Scenarios Model for Driving Collaborative Virtual Environments) is a model and an engine based on petri nets extended with sensors and effectors, enabling the description and execution of complex and interactive scenarios

FUNCTIONAL DESCRIPTION: #SEVEN enables the execution of complex scenarios for driving Virtual Reality applications. #SEVEN's scenarios are based on enhanced Petri net and state machine models which is able to describe and solve intricate event sequences. #SEVEN comes with an editor for creating, editing and remotely controlling and running scenarios. #SEVEN is implemented in C# and can be used as a stand-alone application or as a library. An integration to the Unity3D engine, compatible with MiddleVR, also exists.

Release Functional Description: Adding state machine handling for scenario description in addition to the already existing petri net format. Improved scenario editor

- Participants: Florian Nouviale, Valérie Gouranton, Bruno Arnaldi, Vincent Goupil, Emeric Goga, Carl-Johan Jorgensen, Adrien Reuzeau and Alexandre Audinot
- Contact: Valérie Gouranton
- Publications: Versatile Scenario Guidance for Collaborative Virtual Environments - Roles in Collaborative Virtual Environments for Training - Actions sequencing incollaborative virtual environment - Short Paper: #SEVEN, a Sensor Effector Based Scenarios Model for Driving Collaborative Virtual Environment
- URL: https://bil.inria.fr/fr/software/view/2528/tab

6.3. OpenVIBE

Keywords: Neurosciences - Interaction - Virtual reality - Health - Real time - Neurofeedback - Brain-Computer Interface - EEG - 3D interaction

Functional Description: OpenViBE is a free and open-source software platform devoted to the design, test and use of Brain-Computer Interfaces (BCI). The platform consists of a set of software modules that can be integrated easily and efficiently to design BCI applications. The key features of OpenViBE software are its modularity, its high-performance, its portability, its multiple-users facilities and its connection with high-end/VR displays. The designer of the platform enables to build complete scenarios based on existing software modules using a dedicated graphical language and a simple Graphical User Interface (GUI). This software is available on the Inria Forge under the terms of the AGPL licence, and it was officially released in June 2009. Since then, the OpenViBE software has already been downloaded more than 60000 times, and it is used by numerous laboratories, projects, or individuals worldwide. More information, downloads, tutorials, videos, documentations are available on the OpenViBE website.

- Participants: Cedric Riou, Thierry Gaugry, Anatole Lécuyer, Fabien Lotte, Jussi Tapio Lindgren, Laurent Bougrain, Maureen Clerc and Théodore Papadopoulo
- Partners: INSERM - GIPSA-Lab
- Contact: Anatole Lécuyer
- URL: http://openvibe.inria.fr

6.4. Platforms

6.4.1. Immerstar

- Participants: Florian Nouviale, Ronan Gaugne
- URL: http://www.irisa.fr/immersia/

With the two virtual reality technological platforms Immersia and Immermove, grouped under the name Immerstar, the team has access to high-level scientific facilities. This equipment benefits the research teams of the center and has allowed them to extend their local, national and international collaborations. The Immerstar platform was granted by an Inria funding for the 2015-2019 period which had enabled several important evolutions. In particular, in 2018, a haptic system covering the entire volume of the Immersia platform was installed, allowing various configurations from single haptic device usage to dual haptic devices usage with either one or two users. In addition, a motion platform designed to introduce motion feedback for powered wheelchair simulations has also been incorporated (see Figure 2).

We celebrated the twentieth anniversary of the Immersia platform in November 2019 by inaugurating the new haptic equipment. We proposed scientific presentations and received 150 participants, and visits for the support services in which we received 50 persons.

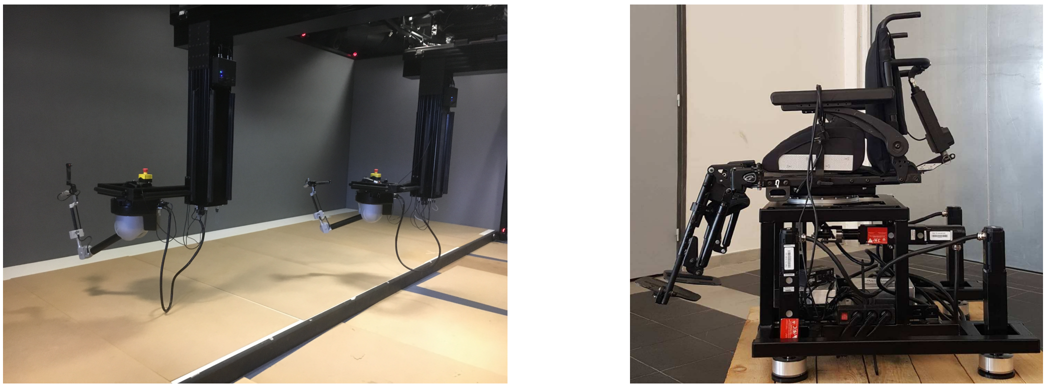

Figure 2. Immersia platform: (Left) "Scale-One" Haptic system for one or two users. (Right) Motion platform for a powered wheelchair simulation.

Figure 3. (Left) The LSI project in Immersia. (Right) The LSI project in Ars Electronica.

Immersia hosted and supported several projects and experiments during the year such as the Adapt [34], Sunset [2] or Introspect ([19], [29]) projects. Moreover, the platform was involved in the multidisciplinary project LSI led by the invited professor Franz Fischnaller from the Academy of Fine Arts of Torino. The project was implemented in Immersia with the support of the Immersia staff and deployed in the Ars Electronica center 3.

7. New Results

7.1. Virtual Reality Tools and Usages

7.1.1. Studying the Mental Effort in Virtual Versus Real Environments

Participants: Tiffany Luong, Ferran Argelaguet, Anatole Lécuyer [contact].

Is there an effect of Virtual Reality (VR) Head-Mounted Display (HMD) on the user's mental effort? In this work, we compare the mental effort in VR versus in real environments [26]. An experiment (N=27) was conducted to assess the effect of being immersed in a virtual environment (VE) using a HMD on the user's mental effort while performing a standardized cognitive task (the wellknown N-back task, with three levels of difficulty (1,2,3)). In addition to test the effect of the environment (i.e., virtual versus real), we also explored the impact of performing a dual task (i.e., sitting versus walking) in both environments on mental effort. The mental effort was assessed through self-reports, task performance, behavioural and physiological measures. In a nutshell, the analysis of all measurements revealed no significant effect of being immersed in the VE on the users' mental effort. In contrast, natural walking significantly increased the users' mental effort. Taken together, our results support the fact that there is no specific additional mental effort related to the immersion in a VE using a VR HMD.

7.1.2. Influence of Personality Traits and Body Awareness on the Sense of Embodiment in VR

Participants: Diane Dewez, Rebecca Fribourg, Ferran Argelaguet, Anatole Lécuyer [contact].

With the increasing use of avatars in virtual reality, it is important to identify the factors eliciting the sense of embodiment. This work reports an exploratory study aiming at identifying internal factors (personality traits and body awareness) that might cause either a resistance or a predisposition to feel a sense of embodiment towards a virtual avatar. To this purpose, we conducted an experiment (n=123) in which participants were immersed in a virtual environment and embodied in a gender-matched generic virtual avatar through a head-mounted display [16]. After an exposure phase in which they had to perform a number of visuomotor tasks, a virtual character entered the virtual scene and stabbed the participants' virtual hand with a knife (see Figure 4). The participants' sense of embodiment was measured, as well as several personality traits (Big Five traits and locus of control) and body awareness, to evaluate the influence of participants' personality on the acceptance of the virtual body. The major finding is that the locus of control is linked to several components of embodiment: the sense of agency is positively correlated with an internal locus of control and the sense of body ownership is positively correlated with an external locus of control. Taken together, our results suggest that the locus of control could be a good predictor of the sense of embodiment. Yet, further studies are required to confirm these results.
This work was done in collaboration with the MimeTIC team.

7.1.3. Consumer perceptions and purchase behavior of imperfect fruits and vegetables in VR

Participants: Jean-Marie Normand, Guillaume Moreau [contact].

This study investigates the effects of fruits and vegetables (FaVs) abnormality on consumer perceptions and purchasing behavior [9]. For the purposes of this study, a virtual grocery store was created with a fresh FaVs section, where 142 participants became immersed using an Oculus Rift DK2 Head-Mounted Display (HMD) software. Participants were presented either normal, slightly misshapen, moderately misshapen or severely misshapen FaVs. The study findings indicate that shoppers tend to purchase a similar number of FaVs whatever their level of deformity. However, perceptions of the appearance and quality of the FaVs depend on the degree of abnormality. Moderately misshapen FaVs are perceived as significantly better than those that are heavily misshapen but also "slightly" misshapen (except for the appearance of fruits).

Figure 4. From left to right: an example of a trajectory to draw during the experimental task; A view of the scene from behind; Another virtual character stabbing the participants' virtual hand at the end of the experiment to measure their response to the threat on their virtual body.

This work was done in collaboration with Audecia Recherce, the University of Reading and the University of Tokyo.

7.1.4. Am I better in VR with a real audience?

Participants: Romain Terrier, Valérie Gouranton [contact], Bruno Arnaldi.

We designed an experimental study to investigate the effects of a real audience on social inhibition [33]. The study is a virtual reality (VR) and multiuser application (see Figure 5). The experience is locally or remotely shared. The application engages one user and a real audience (i.e., local or remote conditions). A control condition is designed where the user is alone (i.e., alone condition). The objective performance (i.e., type and answering time) of users, when performing a categorization of numbers task in VR, is used to explore differences between conditions. In addition to this, the perceptions of others, the stress, the cognitive workload, and the presence of each user have been compared in relation to the location of the real audience. The results showed that in the presence of a real audience (in the local and remote conditions), user performance is affected by social inhibitions. Furthermore, users are even more influenced when the audience does not share the same room, despite others are less perceived.
This work was done in collaboration with IRT B COM.

Figure 5. Experimental setup for the social inhibition experiment in Virtual Reality.

7.1.5. Create by Doing – Action sequencing in VR

Participants: Flavien Lécuyer, Valérie Gouranton [contact], Adrien Reuzeau, Ronan Gaugne, Bruno Arnaldi.

In every virtual reality application, there are actions to perform, often in a logical order. This logical ordering can be a predefined sequence of actions, enriched with the representation of different possibilities, which we refer to as a scenario. Authoring such a scenario for virtual reality is still a difficult task, as it needs both the expertise from the domain expert and the developer. We propose [28] to let the domain expert create in virtual reality the scenario by herself without coding, through the paradigm of creating by doing (see Figure 6). The domain expert can run an application, record the sequence of actions as a scenario, and then reuse this scenario for other purposes, such as an automatic replay of the scenario by a virtual actor to check the obtained scenario, the injection of this scenario as a constraint or a guide for a trainee, or the monitoring of the scenario unfolding during a procedure.

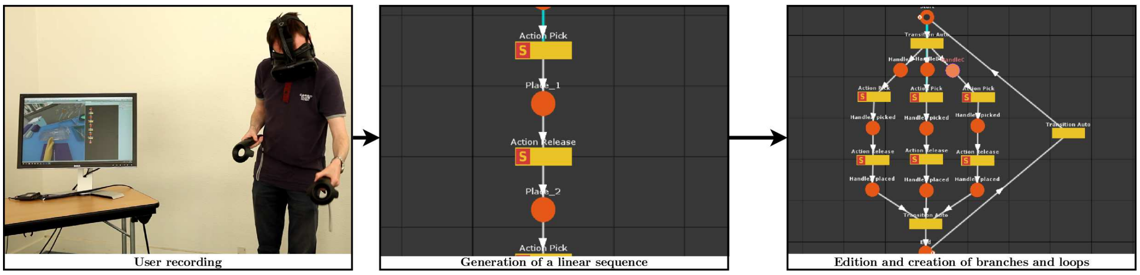

Figure 6. The proposed workflow for the creation of scenarios

7.1.6. Help! I Need a Remote Guide in my Mixed Reality Collaborative Environment

Participants: Valérie Gouranton [contact], Bruno Arnaldi.

The help of a remote expert in performing a maintenance task can be useful in many situations, and can save time as well as money. In this context, augmented reality (AR) technologies can improve remote guidance thanks to the direct overlay of 3D information onto the real world. Furthermore, virtual reality (VR) enables a remote expert to virtually share the place in which the physical maintenance is being carried out. In a traditional local collaboration, collaborators are face-to-face and are observing the same artifact, while being able to communicate verbally and use body language such as gaze direction or facial expression. These interpersonal communication cues are usually limited in remote collaborative maintenance scenarios, in which the agent uses an AR setup while the remote expert uses VR. Providing users with adapted interaction and awareness features to compensate for the lack of essential communication signals is therefore a real challenge for remote MR collaboration. However, this context offers new opportunities for augmenting collaborative abilities, such as sharing an identical point of view, which is not possible in real life. Based on the current task of the maintenance procedure, such as navigation to the correct location or physical manipulation, the remote expert may choose to freely control his/her own viewpoint of the distant workspace, or instead may need to share the viewpoint of the agent in order to better understand the current situation. In this work, we first focus on the navigation task, which is essential to complete the diagnostic phase and to begin the maintenance task in the correct location [8]. We then present a novel interaction paradigm, implemented in an early prototype, in which the guide can show the operator the manipulation gestures required to achieve a physical task that is necessary to perform the maintenance procedure. These concepts are evaluated, allowing us to provide guidelines for future systems targeting efficient remote collaboration in MR environments.
This work was done in collaboration with IRT B COM and UMR Lab-STICC, France.

7.1.7. Learning procedural skills with a VR simulator: An acceptability study

Participants: Valérie Gouranton [contact], Bruno Arnaldi.

Virtual Reality (VR) simulation has recently been developed and has improved surgical training. Most VR simulators focus on learning technical skills and few on procedural skills. Studies that evaluated VR simulators focused on feasibility, reliability or easiness of use, but few of them used a specific acceptability measurement tool. The aim of the study was to assess acceptability and usability of a new VR simulator for procedural skill training among scrub nurses, based on the Unified Theory of Acceptance and Use of Technology (UTAUT) model. The simulator training system was tested with a convenience sample of 16 non-expert users and 13 expert scrub nurses from the neurosurgery department of a French University Hospital. The scenario was designed to train scrub nurses in the preparation of the instrumentation table for a craniotomy in the operating room (OR). Acceptability of the VR simulator was demonstrated with no significant difference between expert scrub nurses and non-experts. There was no effect of age, gender or expertise. Workload, immersion and simulator sickness were also rated equally by all participants. Most participants stressed its pedagogical interest, fun and realism, but some of them also regretted its lack of visual comfort. This VR simulator designed to teach surgical procedures can be widely used as a tool in initial or vocational training [2], [43].
This work was achieved in collaboration with Univ. Rennes 2-LP3C, LTSI and the Hycomes team.

7.1.8. The Anisotropy of Distance Perception in VR

Participants: Etienne Peillard, Anatole Lécuyer, Ferran Argelaguet, Jean-Marie Normand, Guillaume Moreau [contact].

The topic of distance perception has been widely investigated in Virtual Reality (VR). However, the vast majority of previous work mainly focused on distance perception of objects placed in front of the observer. Then, what happens when the observer looks on the side? In this work, we study differences in distance estimation when comparing objects placed in front of the observer with objects placed on his side [31]. Through a series of four experiments (n=85), we assessed participants' distance estimation and ruled out potential biases. In particular, we considered the placement of visual stimuli in the field of view, users' exploration behavior as well as the presence of depth cues. For all experiments a two-alternative forced choice (2AFC) standardized psychophysical protocol was employed, in which the main task was to determine the stimuli that seemed to be the farthest one. In summary, our results showed that the orientation of virtual stimuli with respect to the user introduces a distance perception bias: objects placed on the sides are systematically perceived farther away than objects in front. In addition, we could observe that this bias increases along with the angle, and appears to be independent of both the position of the object in the field of view as well as the quality of the virtual scene. This work sheds a new light on one of the specificities of VR environments regarding the wider subject of visual space theory. Our study paves the way for future experiments evaluating the anisotropy of distance perception in real and virtual environments.

7.1.9. Study of Gaze and Body Segments Temporal Reorientation Behaviour in VR

Participants: Hugo Brument, Ferran Argelaguet [contact].

This work investigates whether the body anticipation synergies in real environments (REs) are preserved during navigation in virtual environments (VEs). Experimental studies related to the control of human locomotion in REs during curved trajectories report a top-down body segments reorientation strategy, with the reorientation of the gaze anticipating the reorientation of head, the shoulders and finally the global body motion [12]. This anticipation behavior provides a stable reference frame to the walker to control and reorient his/her body segments according to the future walking direction. To assess body anticipation during navigation in VEs, we conducted an experiment where participants, wearing a head-mounted display, performed a lemniscate trajectory in a virtual environment (VE) using five different navigation techniques, including walking, virtual steering (head, hand or torso steering) and passive navigation. For the purpose of this experiment, we designed a new control law based on the power-law relation between speed and curvature during human walking. Taken together, our results showed a similar ordered top-down sequence of reorientation of the gaze, head and shoulders during curved trajectories for all the evaluated techniques. However, the anticipation mechanism was significantly higher for the walking condition compared to the others. Finally, the results work pave the way to the better understanding of the underlying mechanisms of human navigation in VEs and to the design of navigation techniques more adapted to humans.

This work was done in collaboration with the MimeTIC team and the Interactive Media Systems Group (TU Wien, Vienna, Austria).

7.1.10. User-centered design of a multisensory power wheelchair simulator

Participants: Guillaume Vailland, Valérie Gouranton [contact].

Autonomy and social inclusion can reveal themselves everyday challenges for people experiencing mobility impairments. These people can benefit from technical aids such as power wheelchairs to access mobility and overcome social exclusion. However, power wheelchair driving is a challenging task which requires good visual, cognitive and visuo-spatial abilities. Besides, a power wheelchair can cause material damage or represent a danger of injury for others or oneself if not operated safely. Therefore, training and repeated practice are mandatory to acquire safe driving skills to obtain power wheelchair prescription from therapists. However, conventional training programs may reveal themselves insufficient for some people with severe impairments. In this context, Virtual Reality offers the opportunity to design innovative learning and training programs while providing realistic wheelchair driving experience within a virtual environment. In line with this, we propose a user-centered design of a multisensory power wheelchair simulator [34]. This simulator addresses classical virtual experience drawbacks such as cybersickness and sense of presence by combining 3D visual rendering, haptic feedback and motion cues. The simulator was showcased in the SOFMER conference [37].
This work has been done in collaboration with Rainbow team.

Figure 7. Wheelchair simulator.

7.1.11. Machine Learning Based Interaction Technique Selection For 3D User Interfaces

Participant: Bruno Arnaldi [contact].

A 3D user interface can be adapted in multiple ways according to each user's needs, skills and preferences. Such adaptation can consist in changing the user interface layout or its interaction techniques. Personalization systems which are based on user models can automatically determine the configuration of a 3D user interface in order to fit a particular user. In this work, we proposed to explore the use of machine learning in order to propose a 3D selection interaction technique adapted to a target user [23]. To do so, we built a dataset with 51 users on a simple selection application in which we recorded each user profile, his/her results to a

2D Fitts Law based pre-test and his/her preferences and performances on this application for three different interaction techniques. Our machine learning algorithm based on Support Vector Machines (SVMs) trained on this dataset proposes the most adapted interaction technique according to the user profile or his/her result to the 2D selection pre-test. Our results suggest the interest of our approach for personalizing a 3D user interface according to the target user but it would require a larger dataset in order to increase the confidence about the proposed adaptations.

7.1.12. The 3DUI Contest 2019

Participants: Hugo Brument, Rebecca Fribourg, Gerard Gallagher, Thomas Howard, Flavien Lécuyer, Tiffany Luong, Victor Mercado, Etienne Peillard, Xavier de Tinguy, Maud Marchal [contact].

Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario
In this work, we present the design of ten different 3D user interactions using passive haptics and embedded in an escape game scenario in which users have to escape from a pyramid in a limited time [11]. Our solution is innovative by its modularity, allowing interactions with virtual objects using tangible props manipulated either directly using the hands and feet or indirectly through a single prop held in the hand, in order to perform several interactions with the virtual environment (VE). We also propose a navigation technique based on the "impossible spaces" design, allowing users to naturally walk through several overlapping rooms of the VE. All together, our different interaction techniques allow the users to solve several enigmas built into a challenging scenario inside a pyramid.

7.2. Augmented Reality Tools and Usages

7.2.1. Authoring AR by AR, abstraction and libraries

Participants: Flavien Lécuyer, Valérie Gouranton [contact], Adrien Reuzeau, Ronan Gaugne, Bruno Arnaldi.

The demand for augmented reality applications is rapidly growing. In many domains, we observe a new interest for this technology, stressing the need for more efficient ways of producing augmented content. Similarly to virtual reality, interactive objects in augmented reality are a powerful means to improve the experience. While it is now well democratized for virtual reality, interactivity is still finding its way into augmented reality. To open the way to this interactive augmented reality, we designed a new methodology for the management of the interactions in augmented reality, supported by an authoring tool for the use by designers and domain experts [27]. This tool makes the production of interactive augmented content faster, while being scalable to the needs of each application. Usually in the creation of applications, a large amount of time is spent through discussions between the designer (or the domain expert), carrying the needs of the application, and the developer, holding the knowledge to create it (see Figure 8). Thanks to our tool, we reduce this time by allowing the designer to create an interactive application, without having to write a single line of code.

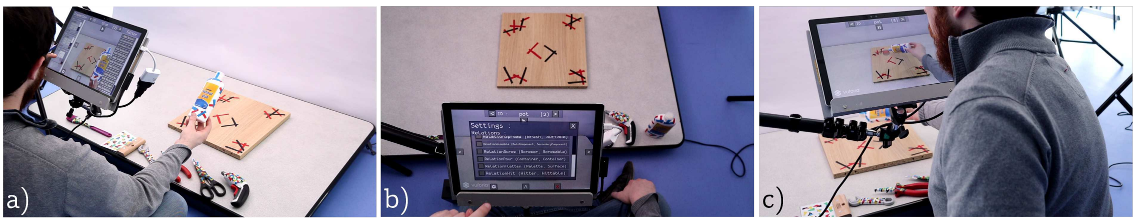

Figure 8. From left to right, the user (a) adds an interactive behaviour on a bottle of glue, (b) imports the interactions in the environment, and (c) uses the interaction to pour the virtual glue from the real bottle into a virtual pot

7.2.2. Studying Exocentric Distance Perception in Optical See-Through AR

Participants: Etienne Peillard, Ferran Argelaguet, Jean-Marie Normand, Anatole Lécuyer, Guillaume Moreau [contact].

While perceptual biases have been widely investigated in Virtual Reality (VR), very few studies have considered the challenging environment of Optical See-through Augmented Reality (OST-AR). Moreover, regarding distance perception, existing works mainly focus on the assessment of egocentric distance perception, i.e. distance between the observer and a real or a virtual object. In this work, we studied exocentric distance perception in AR, hereby considered as the distance between two objects, none of them being directly linked to the user. We report a user study (n=29) aiming at estimating distances between two objects lying in a frontoparallel plane at 2.1m from the observer (i.e. in the medium-field perceptual space). Four conditions were tested in our study: real objects on the left and on the right of the participant (called real-real), virtual objects on both sides (virtual-virtual), a real object on the left and a virtual one on the right (real-virtual) and finally a virtual object on the left and a real object on the right (virtual-real). Participants had to reproduce the distance between the objects by spreading two real identical objects presented in front of them (see Figure 9). The main findings of this study are the overestimation (20%) of exocentric distances for all tested conditions. Surprisingly, the real-real condition was significantly more overestimated (by about 4%,p=.0166) compared to the virtual-virtual condition, i.e. participants obtained better estimates of the exocentric distance for the virtual-virtual condition. Finally, for the virtual-real/real-virtual conditions, the analysis showed a non-symmetrical behavior, which suggests that the relationship between real and virtual objects with respect to the user might be affected by other external factors. Considered together, these unexpected results illustrate the need for additional experiments to better understand the perceptual phenomena involved in exocentric distance perception with real and virtual objects [30].

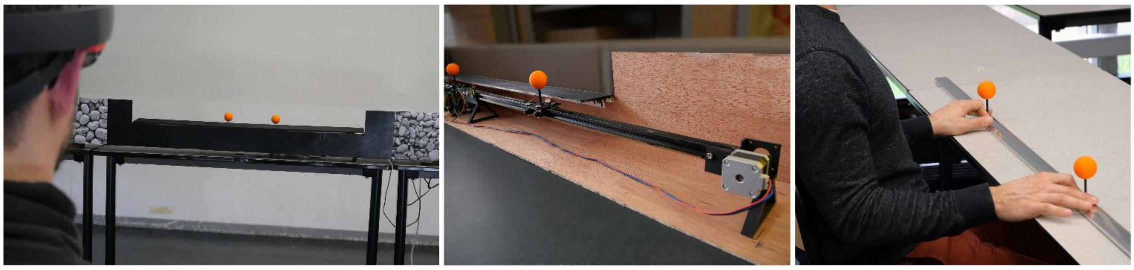

Figure 9. Left, bench displaying two real spheres. The hinge-actuated moving panel, opened here, could be automatically opened/closed to reveal/hide the visual stimuli. Center, one of the two rails of the bench, seen from behind. An orange sphere is attached on top of a trolley that can slide on the rail. The trolley is moved by a stepper motor through a belt. The other half of the bench is symmetrical. Right, participants could provide the perceived exocentric distance by placing two sliding spheres. After the participants placed the spheres the system automatically took a picture of both spheres which was used to measure the distance between both spheres.

7.2.3. Influence of virtual objects' shadows and lighting coherence in AR

Participants: Etienne Peillard, Jean-Marie Normand, Guillaume Moreau [contact].

This work focuses on how virtual objects' shadows as well as differences in alignment between virtual and real lighting influence distance perception in optical see-through (OST) augmented reality (AR) [5]. Four hypotheses are pro-posed: (H1) Participants underestimate distances in OST AR; (H2) Virtual objects' shadows improve distance judgment accuracy in OST AR; (H3) Shadows with different realism levels have different influence on distance perception in OST AR; (H4) Different levels of lighting misalignment between real and virtual lights have different influence on distance perception in OST AR scenes. Two experiments were designed with an OST head mounted display(HMD), the Microsoft HoloLens. Participants had to match the position of a virtual object displayed in the OST-HMD with a real target. Distance judgment accuracy was recorded under the different shadows and lighting conditions.The results validate hypotheses H2 and H4 but surprisingly showed no impact of the shape of virtual shadows on distance judgment accuracy thus rejecting hypothesis H3. Regarding hypothesis H1, we detected a trend toward underestimation; given the high variance of the data, more experiments are needed to confirm this result. Moreover, the study also reveals that perceived distance errors and completion time of trials increase along with targets' distance.

7.2.4. A study on differences in human perception in AR

Participants: Jean-Marie Normand, Guillaume Moreau [contact].

With the recent growth in the development of augmented reality (AR) technologies, it is becoming important to study human perception of AR scenes. In order to detect whether users will suffer more from visual and operator fatigue when watching virtual objects through optical see-through head-mounted displays (OST-HMDs), compared with watching real objects in the real world, we propose a comparative experiment including a virtual magic cube task and a real magic cube task [4]. The scores of the subjective questionnaires (SQ) and the values of the critical flicker frequency (CFF) were obtained from 18 participants. In our study, we use several electrooculogram (EOG) and heart rate variability (HRV) measures as objective indicators of visual and operator fatigue. Statistical analyses were performed to deal with the subjective and objective indicators in the two tasks. Our results suggest that participants were very likely to suffer more from visual and operator fatigue when watching virtual objects presented by the OST-HMD. In addition, the present study provides hints that HRV and EOG measures could be used to explore how visual and operator fatigue are induced by AR content. Finally, three novel HRV measures are proposed to be used as potential indicators of operator fatigue.

This work was done in collaboration with the Beijing Engineering Research Center of Mixed Reality and Advanced Display (School of Optics and Photonics, Beijing Institute of Technology, Beijing, China) and AICFVE (Beijing Film Academy, Beijing, China).

7.3. Physically-Based Simulation and Haptic Feedback

7.3.1. Design of haptic guides for pre-positioning assistance of a comanipulated needle

Participant: Maud Marchal [contact].

In minimally-invasive procedures like biopsy, the physician has to insert a needle into the tissues of a patient to reach a target. Currently, this task is mostly performed manually and under visual guidance. However, manual needle insertion can result in a large final positioning error of the tip that might lead to misdiagnosis and inadequate treatment. A way to solve this limitation is to use shared control; a gesture assistance paradigm that combines the cognitive skills of the operator with the precision, stamina and repeatability of a robotic or haptic device. In this paper, we propose to assist the physician with a haptic device that holds the needle and generates mechanical guides during the phase of manual needle pre-positioning. In the latter, the physician has to place the tip of the needle on a planned entry point, with a pre-defined angle of incidence. From this pre-operative information and also from intra-operative measurements, we propose to generate haptic cues, known as virtual fixtures, to guide the physician towards the desired position and orientation of the needle. It takes the form of five haptic guides, each one implementing virtual fixtures. We conducted a user study where those guides were compared to the unassisted reference gesture. The most constraining guide, in terms of assisted degrees of freedom, was highlighted as the one that provides the best results in terms of performance and user experience [20], [21].

This work was done in collaboration with the Inria Rainbow team.

7.3.2. An Interactive Physically-based Model for Active Suction Phenomenon Simulation

Participants: Antonin Bernardin, Maud Marchal [contact].

While suction cups are widely used in Robotics, the literature is underdeveloped when it comes to the modelling and simulation of the suction phenomenon (see Figure 10). In this work, we present a novel physically-based approach to simulate the behavior of active suction cups. Our model relies on a novel formulation which assumes the pressure exerted on a suction cup during active control is based on constraint resolution. Our algorithmic implementation uses a classification process to handle the contacts during the suction phenomenon of the suction cup on a surface. Then, we formulate a convenient way for coupling the pressure constraint with the multiple contact constraints. We propose an evaluation of our approach through a comparison with real data, showing the ability of our model to reproduce the behavior of suction cups. Our approach paves the way for improving the design as well as the control of robotic actuators based on suction cups such as vacuum grippers.

This work was done in collaboration with the Inria Defrost team.

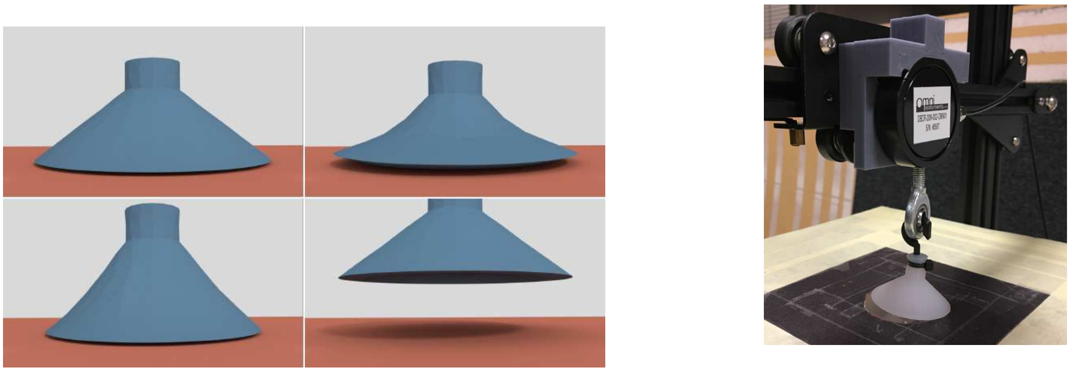

Figure 10. Left, Illustration of our constraint-based physically-based approach for simulating active suction cup phenomenon: (Top) the suction cup is actively stuck to the surface, (Bottom) is is then release until being completely in the air. Right, experimental setup for the force measurements. The suction cup is attached to a force sensor. When it is positioned on a flat surface, its cavity is linked to a vacuum pump with a regulator inbetween.

7.3.3. How different tangible and virtual objects can be while still feeling the same?

Participants: Xavier de Tinguy, Anatole Lécuyer, Maud Marchal [contact].

Tangible objects are used in Virtual Reality to provide human users with distributed haptic sensations when grasping virtual objects. To achieve a compelling illusion, there should be a good correspondence between the haptic features of the tangible object and those of the corresponding virtual one, i.e., what users see in the virtual environment should match as much as possible what they touch in the real world. This work [14] aims at quantifying how similar tangible and virtual objects need to be, in terms of haptic perception, to still feel the same. As it is often not possible to create tangible replicas of all the virtual objects in the scene, it is important to understand how different tangible and virtual objects can be without the user noticing (see Figure 11). This paper reports on the just-noticeable difference (JND) when grasping, with a thumb-index pinch, a tangible object which differ from a seen virtual one on three important haptic features: width, local orientation, and curvature. Results show JND values of 5.75%, 43.8%, and 66.66% of the reference shape for the width, local orientation, and local curvature features, respectively. These results will enable researchers in the field of Virtual Reality to use a reduced number of tangible objects to render multiple virtual ones.
This work was done in collaboration with the Inria Rainbow team.

7.3.4. Toward Universal Tangible Objects

Participants: Xavier de Tinguy, Maud Marchal, Anatole Lécuyer [contact].

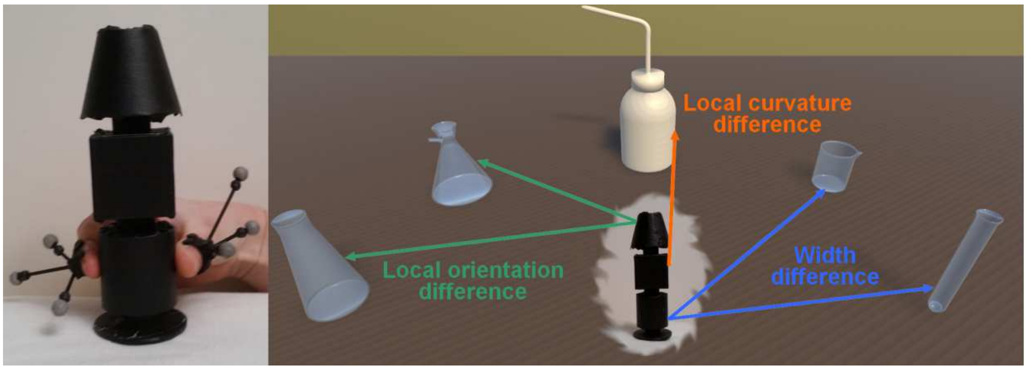

Figure 11. Understanding how different a tangible object (left) can be from virtual objects (right) without the user noticing the mismatch. We focused our study on three specific criteria: width, local orientation, and curvature.

Tangible objects are a simple yet effective way for providing haptic sensations in Virtual Reality. For achieving a compelling illusion, there should be a good correspondence between what users see in the virtual environment and what they touch in the real world. The haptic features of the tangible object should indeed match those of the corresponding virtual one in terms of, e.g., size, local shape, mass, texture. A straightforward solution is to create perfect tangible replicas of all the virtual objects in the scene. However, this is often neither feasible nor desirable. This work [15] presents an innovative approach enabling the use of few tangible objects to render many virtual ones (see Figure 12). The proposed algorithm analyzes the available tangible and virtual objects to find the best grasps in terms of matching haptic sensations. It starts by identifying several suitable pinching poses on the considered tangible and virtual objects. Then, for each pose, it evaluates a series of haptically-salient characteristics. Next, it identifies the two most similar pinching poses according to these metrics, one on the tangible and one on the virtual object. Finally, it highlights the chosen pinching pose, which provides the best matching sensation between what users see and touch. The effectiveness of our approach is evaluated through a user study. Results show that the algorithm is able to well combine several haptically-salient object features to find convincing pinches between the given tangible and virtual objects.
This work was done in collaboration with the Inria Rainbow team.

7.3.5. Investigating the recognition of local shapes using mid-air ultrasound haptics

Participants: Thomas Howard, Gerard Gallagher, Anatole Lécuyer, Maud Marchal [contact].

Mid-air haptics technologies are able to convey haptic sensations without any direct contact between the user and the haptic interface. One representative example of this technology is ultrasound haptics, which uses ultrasonic phased arrays to deliver haptic sensations. Research on ultrasound haptics is only in its beginnings, and the literature still lacks principled perception studies in this domain. This work [22] presents a series of human subject experiments investigating important perceptual aspects related to the rendering of 2D shapes by an ultrasound haptic interface (the Ultrahaptics STRATOS platform, see Figure 13). We carried out four user studies aiming at evaluating (i) the absolute detection threshold for a static focal point rendered via amplitude modulation, (ii) the absolute detection and identification thresholds for line patterns rendered via spatiotemporal modulation, (iii) the ability to discriminate different line orientations, and (iv) the ability to perceive virtual bumps and holes. These results shed light on the rendering capabilities and limitations of this novel technology for 2D shapes.
This work was done in collaboration with the Inria Rainbow team.

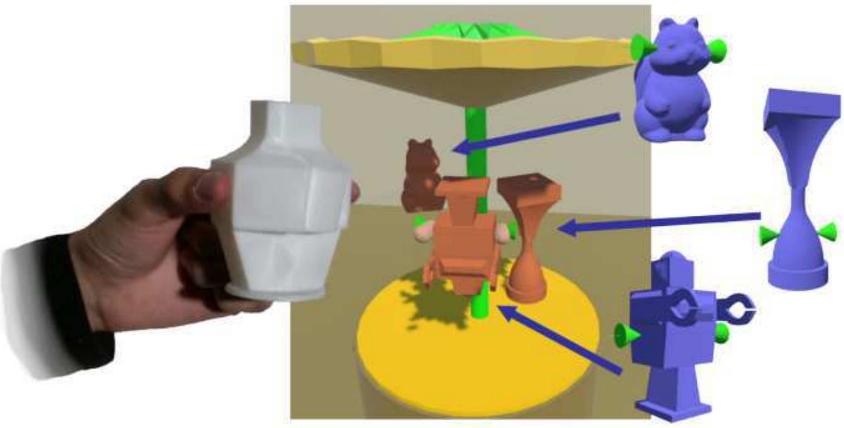

Figure 12. Illustration of our approach through a carousel of virtual objects that can be grasped using a single "universal" tangible object. The user is able to turn the virtual carousel and manipulate the three virtual objects using the suggested pinch poses (in green). These poses are proposed by our algorithm to best match the corresponding haptic pinching sensations on the tangible object.

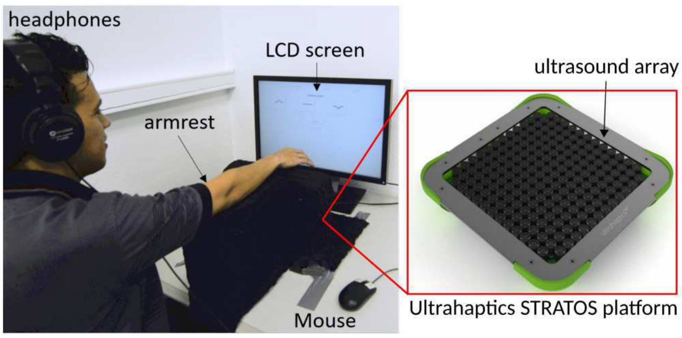

Figure 13. Experimental setup to investigate the recognition of local shapes using mid-air ultrasound haptics.

7.3.6. *Touchy: Tactile Sensations on Touchscreens Using a Cursor and Visual Effects*

Participants: Antoine Costes, Ferran Argelaguet, Anatole Lécuyer [contact].

Haptic enhancement of touchscreens usually involves vibrating motors that produce limited sensations or custom mechanical actuators that are difficult to widespread. In this work, we propose an alternative approach called "Touchy" to induce haptic sensations in touchscreens through purely visual effects [3]. Touchy introduces a symbolic cursor under the user's finger which shape and motion are altered in order to evoke haptic properties. This novel metaphor enables to address four different perceptual dimensions, namely: hardness, friction, fine roughness and macro roughness. Our metaphor comes with a set of seven visual effects that we compared with real texture samples within a user study conducted with 14 participants. Taken together our results show that Touchy is able to elicit clear and distinct haptic properties: stiffness, roughness, reliefs, stickiness and slipperiness.
This work was achieved in collaboration with InterDigital.

7.3.7. *Investigating Tendon Vibration Illusions*

Participants: Salomé Lefranc [contact], Mélanie Cogné, Mathis Fleury, Anatole Lécuyer.

Illusion of movement induced by tendon vibration can be useful in applications such as rehabilitation of neurological impairments. In [40], we investigated whether a haptic proprioceptive illusion induced by a tendon vibration of the wrist congruent to the visual feedback of a moving hand could increase the overall illusion of movement. Tendon vibration was applied on the non-dominant wrist during 3 visual conditions: a moving virtual hand corresponding to the movement that the subjects could feel during the tendon vibration (Moving condition), a static virtual hand (Static condition), or no virtual hand at all (Hidden condition). There was a significant difference between the 3 visual feedback conditions, and the Moving condition was found to induce a higher intensity of illusion of movement and higher sensation of wrist's extension. Therefore, our study demonstrated the potentiation of illusion by visual cues congruent to the illusion of movement. Further steps will be to test the same hypothesis with stroke patients and use our results to develop EEG-based Neurofeedback including vibratory feedback to improve upper limb motor function after a stroke.
This work was achieved in collaboration with CHU Rennes and Inria EMPENN team.

7.4. Brain-Computer Interfaces

7.4.1. *Defining Brain-Computer Interfaces: A Human-Computer Interaction Perspective*

Participants: Hakim Si Mohammed, Ferran Argelaguet, Anatole Lécuyer [contact].

Regardless of the term used to designate them, Brain-Computer Interfaces (BCIs) are "Interfaces" between a user and a computer in the broad sense of the term. This paper aims to discuss how BCIs have been defined in the literature from the day the term was introduced by Jacques Vidal. In [32], from a Human-Computer Interaction perspective, we propose a new definition of Brain-Computer Interfaces as : "any artificial systems that directly converts brain activity into input of a computer process". As they are interfaces, such definition should not include the finality and objective of the system they are used to interact with. To illustrate this, we compared BCIs with other widely used Human-Computer Interfaces, and drew analogies in their conception and purpose.

This work was done in collaboration with the Inria LOKI team.

7.4.2. *A conceptual space for EEG-based brain-computer interfaces*

Participant: Anatole Lécuyer [contact].

Brain-Computer Interfaces have become more and more popular these last years. Researchers use this technology for several types of applications, including attention and workload measures but also for the direct control of objects by the means of BCIs. In [7] we present a first, multidimensional feature space for EEG-based BCI applications to help practitioners to characterize, compare and design systems, which use EEG-based BCIs. Our feature space contains 4 axes and 9 sub-axes and consists of 41 options in total as well as their different combinations. In addition we present the axes of our feature space and we position our feature space regarding the existing BCI and HCI taxonomies. We also showed how our work integrates the past works, and/or complements them.

7.4.3. The use of haptic feedback in Brain-Computer Interfaces and Neurofeedback

Participants: Mathis Fleury, Anatole Lécuyer [contact].

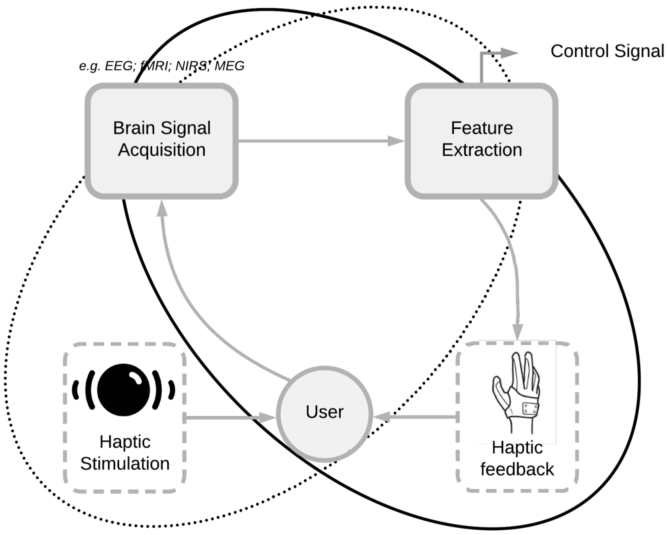

Figure 14. Using haptic feedback in active and reactive Brain-Computer Interfaces (BCI). In active BCI, haptics provide feedback from user's neural activity (black ellipse). In reactive BCI, haptics provide a stimulation to elicit a specific brain activity (black doted ellipse).

Neurofeedback (NF) and brain-computer interfaces are based on the recording of the cerebral activity associated with the requested task and the presentation of a feedback. The subject relies on the given feedback (visual, auditory or haptic) to learn and improve his mental strategy. It is therefore of crucial importance that it must be transmitted optimally. Historically, vision is the most used sensory modality in BCI/NF applications, but its use is raising potential issues. The more and more frequent use of haptic as a feedback modality reveals the limits of visual feedback; indeed, a visual feedback is not suitable in some cases, for individuals with an impaired visual system or during a mental motor imagery task (e.g. requiring a great abstraction). In such case, a haptic feedback would seem more appropriate. Haptic feedback has also been reported to be more engaging than visual feedback. This feedback could also contribute to close the sensory-motor loop. Haptic-based BCI/NF is a promising alternative for the design of the feedback and potentially improve the clinical efficacy of NF. In [38], [39] we have therefore surveyed the recent studies exploiting haptic feedback in BCI and NF.

This work was achieved in collaboration with the Inria EMPENN team.

7.4.4. Efficacy of EEG-fMRI Neurofeedback for stroke rehabilitation: a pilot study

Participants: Giulia Lioi, Mathis Fleury, Anatole Lécuyer [contact].

Recent studies have shown the potential of neurofeedback for motor rehabilitation after stroke. The majority of these NF approaches have relied solely on one imaging technique: mostly on EEG recordings. Recent study have gone further, revealing the potential of integrating complementary techniques such as EEG and fMRI to achieve a more specific regulation. In this exploratory work, multi-session bimodal EEG-fMRI NF for upper limb motor recovery was tested in four stroke patients.The feasibility of the NF training was investigated [41] with respect to the integrity of the cortico-spinal tract (CST), a well-established predictor of the potential for

clinical improvement. Results indicated that patients exhibiting a high degree of integrity of the ipsilesional CST showed significant increased activation of the ipsilesional M1 at the end of the training. These preliminary findings confirm the critical role of the CST integrity for stroke motor recovery and indicate that this is importantly related also to functional brain regulation of the ipsilesional motor cortex.
This work was achieved in collaboration with Inria EMPENN team.

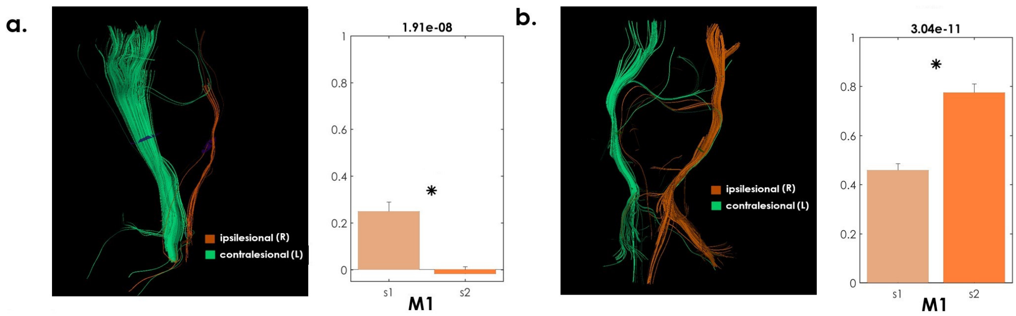

Figure 15. Example of CST reconstruction and primary motor cortex (M1) activation in two patients (a. and b.). Ipsilesional CST is plotted in orange and controlesional CST in green. The bar plot on the right hand side of the figure show the average (and standard error across NF training blocks) of BOLD contrast activation in the primary motor cortex in the first (s1) and second (s2) training session, with relative statistics.

7.4.5. A multi-target motor imagery training using EEG-fMRI Neurofeedback

Participants: Giulia Lioi, Mathis Fleury, Anatole Lécuyer [contact].

Upper limb recovery after stroke is a complex process. Recent studies have revealed the potential of neurofeedback training as an alternative or an aid to traditional therapies. Studies on cerebral plasticity and recovery after stroke indicate that premotor areas should be a preferred target for NF in the most severe patients while M1 stimulation may be more ef for patients with better recovery potential. Moreover, fMRI-NF studies (also on stroke patients) have shown that SMA is a robust correlate of motor imagery, while the activation of M1 is more dif to achieve, especially for short training sessions. Based on these results, in an exploratory work [13], we tested a dynamic NF training more strongly rewarding SMA activation in the NF training session and then increasing the M1 activation contribution in the NF session. We tested this novel approach on four stroke patients in a multisession bimodal EEG-fMRI NF training. To this end, we used an adaptive cortical region of interest (ROI) equal to a weighted combination of ipsilesional SMA and M1 activities and then varied the weights in order guide the patient training towards an improved activation of M1. Four chronic stroke patients with left hemiparesis participated to the study. The experimental protocol included an alternation of bimodal EEG-fMRI NF and unimodal EEG-only NF sessions. Preliminary results, on a short training duration, reveal the potential of a dynamic, multi-target/multimodal NF training approach.
This work was achieved in collaboration with Inria EMPENN team.

7.4.6. Bimodal EEG-fMRI Neurofeedback for upper motor limb rehabilitation

Participants: Giulia Lioi, Mathis Fleury, Anatole Lécuyer [contact].

There is a growing interest in Neurofeedback or Brain computer interfaces for stroke rehabilitation. Integrating EEG and fMRI, two highly complementary imaging modalities, has potential to provide a more specific and efficient stimulation of motor areas. In this exploratory work [25], we tested the feasibility of a multi-session EEG-fMRI NF protocol on four chronic stroke patients, and its potential for upper-limb recovery. All the patients were able to upregulate their activity during NF training with respect to rest in the ipsilesional SMA and M1. Three over four patients showed a significant increase in ipsilesional M1 activation at the end of the protocol. Of these three individuals, two exhibited an increase in FMA-UE score. Preliminary results from this pilot study showed feasibility of bimodal EEG-fMRI in chronic stroke patients and indicated the potential of this training protocol for upper-limb recovery.
This work was achieved in collaboration with Inria EMPENN team.

7.5. Cultural Heritage

7.5.1. Expressive potentials of motion capture in the Vis Insita musical performance

Participants: Ronan Gaugne [contact], Florian Nouviale, Valérie Gouranton.

The electronic music performance project Vis Insita [10] implements the design of experimental instrumental interfaces based on optical motion capture technology with passive infrared markers (MoCap), and the analysis of their use in a real scenic presentation context (Figure 16). Because of MoCap's predisposition to capture the movements of the body, a lot of research and musical applications in the performing arts concern dance or the sonification of gesture. For our research, we wanted to move away from the capture of the human body to analyse the possibilities of a kinetic object handled by a performer, both in terms of musical expression, but also in the broader context of a multimodal scenic interpretation.
This work was done in collaboration with Univ. Rennes 2, France.

Figure 16. The Vis Insita performance.

7.5.2. Interactive and Immersive Tools for Point Clouds in Archaeology

Participants: Ronan Gaugne [contact], Quentin Petit, Valérie Gouranton.

A framework is presented for an immersive and interactive 3D manipulation of large point clouds, in the context of an archaeological study [19]. The framework was designed in an interdisciplinary collaboration with archaeologists. We first applied this framework for the study of an 17th-century building of a Real Tennis court (Figure 17). We propose a display infrastructure associated with a set of tools that allows archaeologists to interact directly with the point cloud within their study process. The resulting framework allows an immersive navigation at scale 1:1 in a dense point cloud, the manipulation and production of cut plans and cross sections, and the positioning and visualisation of photographic views. We also apply the same framework to three other archaeological contexts with different purposes, a 13th century ruined chapel, a 19th-century wreck and a cremation urn from the Iron Age.
This work was done in collaboration with UMR CREAAH, France.

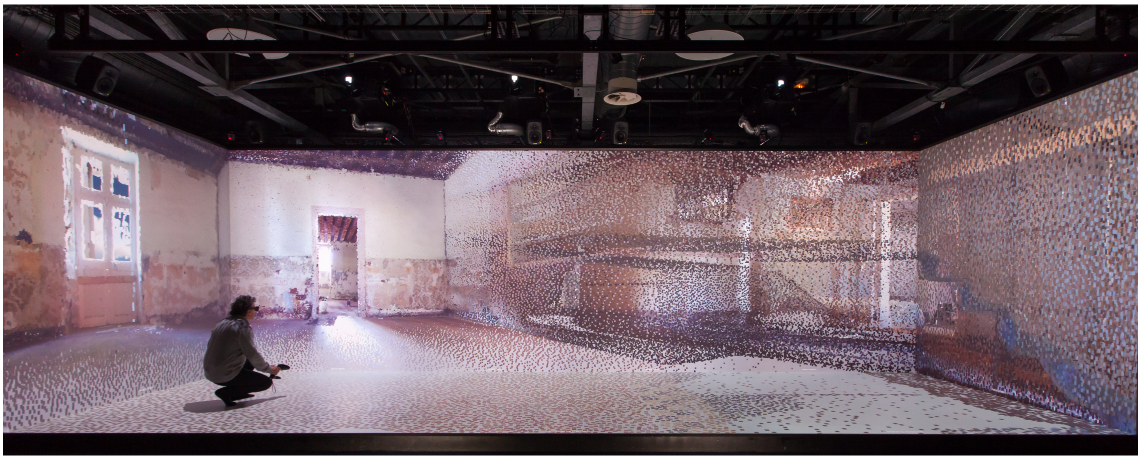

Figure 17. Immersive view of the point cloud of the Real Tennis building.

7.5.3. Making virtual archeology great again (without scientific compromise)

Participants: Ronan Gaugne, Valérie Gouranton [contact].

In the past two decades or so, digital tools have been slowly integrated as part of the archaeological process of information acquisition, analysis, and dissemination. We are now entering a new era, adding the missing piece to the puzzle in order to complete this digital revolution and take archaeology one step further into virtual reality (VR). The main focus of this work is the methodology of digital archaeology that fully integrates virtual reality, from beta testing to interdisciplinary teamwork. After data acquisition and processing necessary to construct the 3D model, we explore the analysis that can be conducted during and after the making or creation of the 3D environment and the dissemination of knowledge. We explain the relevance of this methodology through the case study on the intendant's palace, an 18th century archaeological site in Quebec City, Canada (Figure 18 left). With this experience, we believe that VR can prompt new questions that would never have occurred otherwise and can provide technical advantages in terms of gathering data in the same virtual space (Figure 18 right). We conclude that multidisciplinary input in archaeological research is once again proven essential in this new, inclusive and vast digital structure of possibilities [29].
This work was done in collaboration with UMR CREAAH, Inrap, France and Univ. Laval, Canada.

7.5.4. Evaluation of a Mixed Reality based Method for Archaeological Excavation Support

Participants: Ronan Gaugne [contact], Quentin Petit, Valérie Gouranton.

Figure 18. Left, model of the XVIIth century Palais de l'Intendant. Right, study of the reconstitution of the Palais de L'intendant and its neighborhood inside Immersia

In the context of archaeology, most of the time, micro-excavation for the study of furniture (metal, ceramics...) or archaeological context (incineration, bulk sampling) is performed without complete knowledge of the internal content, with the risk of damaging nested artifacts during the process. The use of medical imaging coupled with digital 3D technologies, has led to significant breakthroughs by allowing to refine the reading of complex artifacts. However, archaeologists may have difficulties in constructing a mental image in 3 dimensions from the axial and longitudinal sections obtained during medical imaging, and in the same way to visualize and manipulate a complex 3D object on screen, and an inability to simultaneously manipulate and analyze a 3D image, and a real object. Thereby, if digital technologies allow a 3D visualization (stereoscopic screen, VR headset ...), they are not without limiting the natural, intuitive and direct 3D perception of the archaeologist on the material or context being studied. We therefore propose a visualization system based on optical see-through augmented reality that associates real visualization of archaeological material with data from medical imaging [18] (see Figure 19). This represents a relevant approach for composite or corroded objects or contexts associating several objects such as cremations. The results presented in the paper identify adequate visualization modalities to allow archaeologist to estimate, with an acceptable error, the position of an internal element in a particular archaeological material, an Iron-Age cremation block inside a urn.
This work was done in collaboration with Inrap, France and AIST (National Institute of Advanced Industrial Science and Technology), Japan.

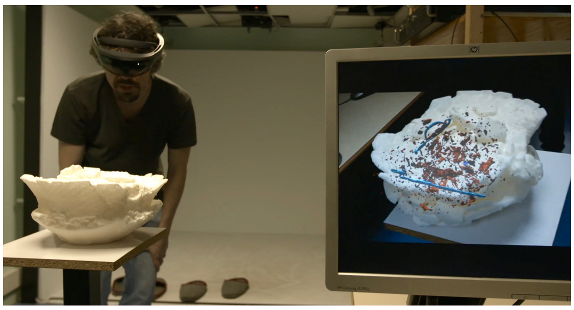

Figure 19. Evaluation of the mixed reality system

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Mensia Technologies

Participant: Anatole Lécuyer.

Mensia Technologies was an Inria start-up company created in November 2012 as a spin-off of Hybrid team. Mensia was focused on wellness and healthcare applications emerging from the BCI and Neurofeedback technologies. The Mensia startup benefited from the team's expertise and of valuable and proprietary BCI research results. Mensia was based in Rennes and Paris. Anatole Lécuyer and Yann Renard (former Inria expert engineer who designed the OpenViBE software architecture and was involved in team projects for 5 years) are co-founders of Mensia Technologies.

The contract between Hybrid and Mensia started in November 2013 and ended in August 2019 with the closing of the company. The contract supported the transfer of several softwares designed by Hybrid team (eg, OpenViBE and StateFinder) to Mensia Technologies for medical and multimedia applications of Mensia.

8.1.2. Orange Labs

Participants: Anatole Lécuyer [contact], Hakim Si-Mohammed, Ferran Argelaguet.

This four months contract between Hybrid and Orange labs (Jan - April 2019) covered the design of a proof of concept of a smart home system controlled using a brain computer interface in and augmented reality context.

8.2. Bilateral Grants with Industry

8.2.1. Orange Labs

Participants: Guillaume Bataille, Bruno Arnaldi, Valérie Gouranton [contact].

This grant started in October 2017. It supports Guillaume Bataille's PhD program with Orange Labs company on "Natural Interactions with IoT using VR/AR".

In the context of this collaboration the following patent has been filled:

- "Dispositif d'affichage portatif de contenu 3D, système et procédé correspondants" (FR1914557), Guillaume Bataille, Bruno Arnaldi, Valérie Gouranton, Jérémy Lacoche. Filed in Dec. 2019.

8.2.2. InterDigital

Participants: Nicolas Olivier, Ferran Argelaguet, Anatole Lécuyer [contact].

This grant started in February 2019. It supports Nicolas's Olivier CIFRE PhD program with InterDigital company on "Avatar Stilization". This PhD is co-supervised with the MimeTIC team.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Labex Cominlabs SUNSET

Participants: Bruno Arnaldi, Valérie Gouranton [contact], Alexandre Audinot, Adrien Reuzeau.

SUNSET is a 4-year Labex Cominlabs project (2016-2020). SUNSET partners are MediCIS-LTSI (coordinator), Hybrid, Hycomes (IRISA/Inria), and CHU Rennes. SUNSET aims at developing an innovative training software suite based on immersive and collaborative virtual reality technology for training and evaluating non-technical skills. This approach will be implemented and evaluated in the context of training neurosurgical scrub nurses. We will notably integrate methods and systems developed in the S3PM project (see bellow). By relying on Human Factors approaches, the project also addresses training and evaluation of interpersonal skills. Whereas the developed technologies and approaches will be generic and adaptable to any surgical specialty, the project will evaluate the developed system within training sessions performed with scrub nurses. We ambition to propose novel approaches for surgical non-technical skill learning and assessment, and to install the developed training factory at the University Hospital of Rennes, and evaluate it with real-scale user studies.

9.1.2. Labex Cominlabs RobotX

Participants: Bruno Arnaldi, Valérie Gouranton [contact], Alexandre Audinot.

RobotX (ROBOT for Intelligent Collaborative Surgery) is a one year Labex Cominlabs project (2019). The partners are MediCIS team from LTSI (INSERM and University of Rennes 1), Hybrid, Rainbow and Hycomes teams from IRISA and Inria Rennes, LP3C Lab - University Rennes 2, REV, ROMAS and PACCE teams from LS2N - Nantes, CHU Rennes, CHU Nantes, ICO (Institut de Cancerologie de l'Ouest). The objective of this exploratory action RobotX was to explore this issue and study initial feasibility of some methodological solutions. The long-term is to develop a new generation of intelligent and collaborative safe surgical robots.

Our contribution in the project was to study the development of Virtual Reality based simulated environments for surgical robotic systems for helping designing, evaluation and training of such systems. The objective was also to evaluate simulations of both technical and non technical. We developed a prototype of the Da Vinci robot with an haptic interface and different simulated tasks. We second studied the relevance of the software environments (#5 and #7) developed in previous projects (S3PM and SUNSET). We set up interactions by adding #5 semantics, which allow the robot arm to pick up objects. We also implemented a "Pick and place" exercise. A #7 scenario has been added to manage the user's actions and know when the exercise is over (Fig. 20).

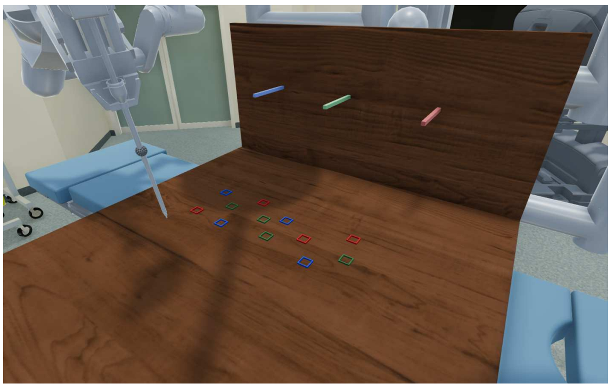

Figure 20. Pick and place exercise using #5 and #7 software

9.1.3. Labex Cominlabs HEMISFER

Participants: Mathis Fleury, Anatole Lécuyer [contact], Giulia Lioi.

HEMISFER is a 6-year project (2013-2019) funded by Labex CominLabs. It involves 4 Inria/IRISA teams (Hybrid, Visages (lead), Panama, Athena) and 2 medical centers: the Rennes Psychiatric Hospital (CHGR) and the Reeducation Department of Rennes Hospital (CHU Pontchaillou). The goal of HEMISFER is to make full use of neurofeedback paradigm in the context of rehabilitation and psychiatric disorders. The major breakthrough will come from the use of a coupling model associating functional and metabolic information from Magnetic Resonance Imaging (fMRI) to Electro-encephalography (EEG) to "enhance" the neurofeedback protocol. Clinical applications concern motor, neurological and psychiatric disorders (stroke, attention-deficit disorder, treatment-resistant mood disorders, etc).

9.1.4. IRT b<>com

Participants: Ferran Argelaguet, Bruno Arnaldi [contact], Valérie Gouranton, Anatole Lécuyer, Maud Marchal, Florian Nouviale.

b<>com is a French Institute of Research and Technology (IRT). The main goal of this IRT is to fasten the development and marketing of tools, products and services in the field of digital technologies. Our team has been regularly involved in collaborations with b<>com within various 3-year projects, such as ImData (on Immersive Interaction) and GestChir (on Augmented Healthcare) which both ended in 2016. Follow-up projects called NeedleWare (on Augmented Healthcare) and VUXIA (on Human Factors) have started respectively in 2016 and 2018.

9.1.5. CNPAO Project

Participants: Valérie Gouranton [contact], Ronan Gaugne.

CNPAO ("Conservatoire Numérique du Patrimoine Archéologique de l'Ouest") is an on-going research project partially funded by the Université Européenne de Bretagne (UEB) and Université de Rennes 1. It involves IRISA/Hybrid and CReAAH. The main objectives are: (i) a sustainable and centralized archiving of 2D/3D data produced by the archaeological community, (ii) a free access to metadata, (iii) a secure access to data for the different actors involved in scientific projects, and (iv) the support and advice for these actors in the 3D data production and exploration through the latest digital technologies, modeling tools and virtual reality systems. This project involves a collaboration with Quentin Petit (SED Inria Rennes).

9.2. National Initiatives

9.2.1. ANR

9.2.1.1. ANR LOBBY-BOT

Participants: Anatole Lécuyer [contact], Maud Marchal, Victor Mercado.

LOBBY-BOT is a 4-year project (2017-2021) funded by the French National Research Agency (ANR). The objective of LOBBY-BOT is to address the scientific challenges of encountered-type haptic devices (ETHD), which are an alternative category of haptic devices relying on a mobile physical prop, usually actuated by a robot, that constantly follows the user hand, and encounter it only when needed. The project follows two research axes: a first one dealing with robot control, and the second one dealing with interaction techniques adapted to ETHD. The involvement of Hybrid relates to the second research axis of the project. The final project prototype will be used to assess the benefits of ETHD when used in an industrial use-case : the perceived quality in an automotive interior.

9.2.2. Inria projects

9.2.2.1. IPL BCI-LIFT

Participants: Anatole Lécuyer [contact], Hakim Si Mohammed.

BCI-LIFT is a 4-year "Inria Project Lab" initiative (2015-2019) funded by Inria for supporting a national research effort on Brain-Computer Interfaces. This joint lab involves several Inria teams: Hybrid, Potioc, Athena, Neurosys, Loki, Demar; as well as external partners: INSERM-Lyon, and INSA Rouen. This project aims at improving several aspects of Brain-Computer Interfaces: learning and adaptation of BCI systems, user interfaces and feedback, training protocols, etc.

9.2.2.2. IPL AVATAR

Participants: Anatole Lécuyer [contact], Ferran Argelaguet, Diane Dewez, Rebecca Fribourg.

AVATAR is a 4-year "Inria Project Lab" initiative (2018-2022) funded by Inria for supporting a national research effort on Avatars and Virtual Embodiment. This joint lab involves several Inria teams: Hybrid, Potioc, Loki, Mimetic, Graphdeco, Morpheo; as well as external partners: Univ. Bacelona, Faurecia and Technicolor companies. This project aims at improving several aspects of Avatars in immersive applications: reconstruction, animation, rendering, interaction, multi-sensory feedback, etc.

9.2.2.3. IPL NAVISCOPE

Participants: Ferran Argelaguet [contact], Gwendal Fouché.

NAVISCOPE is a 4-year "Inria Project Lab" initiative (2018-2022) funded by Inria for supporting a national research effort on image-guided navigation and visualization of large data sets in live cell imaging and microscopy. This joint lab involves several Inria teams: Serpico, Aviz, Beagle, Hybrid, Mosaic, Parietal, Morpheme; as well as external partners: INRA and Institute Curie. This project aims at improving visualization and machine learning methods in order to provide systems capable to assist the scientist to obtain a better understanding of massive amounts of information.

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. IMAGINE

Participants: Maud Marchal [contact], Thierry Gaugry, Romain Lagneau, Antonin Bernardin.

Title: IMAGINE - Robots Understanding Their Actions by Imagining Their Effects

Programm: H2020

Duration: January 2017 - December 2020

Coordinator: Univ. Innsbruck (Austria)

Partners:

- Univ. Innsbruck (Austria)
- Univ. Göttingen (Germany)
- Karlsruhe Institute of Technology (Germany)
- INSA Rennes (France)
- Institute of Robotics and Industrial Informatics (Spain)
- Univ. Bogazici (Turkey)
- Electro Cycling (Germany)

Inria contact: Maud Marchal

Abstract: Today's robots are good at executing programmed motions, but they do not understand their actions in the sense that they could automatically generalize them to novel situations or recover from failures. IMAGINE seeks to enable robots to understand the structure of their environment and how it is affected by its actions. "Understanding" here means the ability of the robot (a) to determine the applicability of an action along with parameters to achieve the desired effect, and (b) to discern to what extent an action succeeded, and to infer possible causes of failure and generate recovery actions. The core functional element is a generative model based on an association engine and a physics simulator. "Understanding" is given by the robot's ability to predict the effects of its actions, before and during their execution. This allows the robot to choose actions and parameters based on their simulated performance, and to monitor their progress by comparing observed to simulated behavior. This scientific objective is pursued in the context of recycling of electromechanical appliances. Current recycling practices do not automate disassembly, which exposes humans to hazardous materials, encourages illegal disposal, and creates significant threats to environment and health, often in third countries. IMAGINE will develop a TRL-5 prototype that can autonomously disassemble prototypical classes of devices, generate and execute disassembly actions for unseen instances of similar devices, and recover from certain failures. For robotic disassembly, IMAGINE will develop a multi-functional gripper capable of multiple types of manipulation without tool changes. IMAGINE raises the ability level of robotic systems in core areas of the work programme, including adaptability, manipulation, perception, decisional autonomy, and cognitive ability. Since only one-third of EU e-waste is currently recovered, IMAGINE addresses an area of high economical and ecological impact.

9.3.1.2. H-REALITY

Participants: Anatole Lécuyer, Maud Marchal [contact], Thomas Howard, Gerard Gallagher.

Title: H-REALITY

Programm: H2020 - Fet Open

Duration: 2018 - 2021

Coordinator: Univ. Birmingham (UK)

Partners:

Univ. Birmingham (UK)

CNRS (France),

TU Delft (Netherlands),

ACTRONIKA (France),

ULTRAHAPTICS (UK)

Inria contact: Maud Marchal

Abstract: The vision of H-REALITY is to be the first to imbue virtual objects with a physical presence, providing a revolutionary, untethered, virtual-haptic reality: H-Reality. This ambition 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 unteathered 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 transform online interactions; dangerous machinery will be operated virtually from the safety of the home, and surgeons will hone their skills on thin air.

9.3.1.3. TACTILITY

Participants: Ferran Argelaguet [contact], Anatole Lécuyer, Maud Marchal, Sebastian Vizcay.

Title: Tactility

Programm: H2020 - ICT 25

Duration: July 2019 - June 2022

Coordinator: Fundación Tecnalia Research and Innovation (Spain)

Partners:

Aalborg University (Netherlands)

Universita Degli Studi di Genova (Itali),

Tecnalia Servia (Servia),

Universitat de Valencia (Spain),

Manus Machinae B.V. (Netherlands),

Smartex S.R.L (Italy),

Immersion (France)

Inria contact: Ferran Argelaguet

Abstract: TACTILITY is a multidisciplinary innovation and research action with the overall aim of including rich and meaningful tactile information into the novel interaction systems through technology for closed-loop tactile interaction with virtual environments. By mimicking the characteristics of the natural tactile feedback, it will substantially increase the quality of immersive VR experience used locally or remotely (tele-manipulation). The approach is based on transcutaneous electro-tactile stimulation delivered through electrical pulses with high resolution spatio-temporal distribution. To achieve it, significant development of technologies for transcutaneous stimulation, textile-based multi-pad electrodes and tactile sensation electronic skin, coupled with ground-breaking research of perception of elicited tactile sensations in VR, is needed. The key novelty is in the combination of: 1) the ground-breaking research of perception of electrotactile stimuli for the identification of the stimulation parameters and methods that evoke natural like tactile sensations, 2) the advanced hardware, that will integrate the novel high-resolution electrotactile stimulation system and state of the art artificial electronic skin patches with smart textile technologies and VR control devices in a wearable mobile system, and 3) the novel firmware, that handles real-time encoding and transmission of tactile information from virtual objects in VR, as well as from the distant tactile sensors (artificial skins) placed on robotic or human hands. Proposed research and innovation action would result in a next generation of interactive systems with higher quality experience for both local and remote (e.g., tele-manipulation) applications. Ultimately, TACTILITY will enable high fidelity experience through low-cost, user friendly, wearable and mobile technology.

9.3.1.4. Interreg ADAPT

Participants: Valérie Gouranton [contact], Bruno Arnaldi, Ronan Gaugne, Florian Nouviale, Yoren Gaffary, Alexandre Audinot.

Program: Interreg VA France (Channel) England

Project acronym: ADAPT

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

Duration: 01/2017 - 06/2021

Coordinator: ESIGELEC/IRSEEM Rouen

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

Inria contact: Valérie Gouranton

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

Collaboration with Rainbow team.

9.4. International Initiatives

9.4.1. Informal International Partners

- Dr. Takuji Narumi and Prof. Michitaka Hirose from University of Tokyo (Japan), on "Virtual Embodiment"

- Dr. Hannes Kaufmann from Technical University Wien (Austria), on "3D Navigation in Virtual Environments"
- Prof. Reinhold Scherer from Graz University (Austria), on "Brain-Computer Interfaces and Augmented Reality"
- Prof. Jose Millan from Ecole Polytechnique Fédérale de Lausanne (Switzerland), on "Brain-Computer Interfaces and Sports"
- Dr. Mai Otsuki from AIST (Japan) on "Mixed Reality for Cultural Heritage"
- Dr. Karina Rodriguez Echavarria from University of Brighton (UK) on "Mixed Reality for Cultural Heritage"
- Prof. Franz Fischnaller from Albertina Academia of Fine Art of Torino (Italy) on "Immersive Art"
- Dr. Yuta Itoh from Tokyo Institute of Technology (Japan) on "Perception in Augmented Reality"

9.4.2. Participation in Other International Programs

9.4.2.1. ANR-FRQSC INTROSPECT

Participants: Valérie Gouranton [contact], Bruno Arnaldi, Ronan Gaugne, Flavien Lécuyer, Adrien Reuzeau.

INTROSPECT is a 3-year project funded by French ANR and "Fonds de Recherche Société et Culture" (FRQSC) from Quebec region, Canada. This international collaboration involves researchers in computer science and archeology from France and Canada : Hybrid (Inria-IRISA), CReAAH, Inrap, company Image ET, University Laval and INRS-ETE. INTROSPECT aims to develop new uses and tools for archaeologists that facilitate access to knowledge through interactive numerical introspection methods that combine computed tomography with 3D visualization technologies, such as Virtual Reality, tangible interactions and 3D printing. The scientific core of the project is the systematization of the relationship between the artefact, the archaeological context, the digital object and the virtual reconstruction of the archaeological context that represents it and its tangible double resulting from the 3D printing. This axiomatization of its innovative methods makes it possible to enhance our research on our heritage and to make use of accessible digital means of dissemination. This approach changes from traditional methods and applies to specific archaeological problems. Several case studies will be studied in various archaeological contexts on both sides of the Atlantic. Quebec museums are also partners in the project to spread the results among the general public.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

- Visit from Yutaro Hirao, Master Student at University of Tokyo (topic: “Virtual Embodiment”). Feb. 2019.
- Visit from Felix Putze, Researcher at University of Bremen (topic: “BCI and AR”). Feb. 2019.
- Visit from Franz Fischnaller, Professor at Academia of Fine Arts Albertina, Torino, Italy (topic: “Cultural Heritage”). From Jun. until Jul. 2019
- Visit from Marie-Anne Paradis, Master Student at University Laval, Québec, Canada (topic: “Cultural Heritage”). From Sept. 2018 until Mar. 2019.
- Visit from Nadia Zenati, Researcher at CDTA, Algeria (topic: “VR and AR”). Oct. 2019

9.5.2. Visits to International Teams

- Jean-Marie Normand spent 2 weeks (1 week in July 2019 and 1 week in September 2019) in the Augmented Vision Laboratory, Tokyo Institute of Technology, Tokyo, Japan.
- Valérie Gouranton and Ronan Gaugne spent 2 weeks, in May 2019, in the Eau-Terre-Environment laboratory of INRS, Québec, Canada where they presented INTROSPECT results in the GMPCA conference organized by the University of Montreal, and in the days of the Canadian Association of Archaeology, organized by the University Laval of Québec.

9.5.2.1. Research Stays Abroad

- Etienne Peillard spent 4 months (from June to October 2019) in the Augmented Vision Laboratory, Tokyo Institute of Technology, Tokyo, Japan.
- Flavien Lécuyer spent 3 months (From May to August 2019) in Vision and Numeric Systems Laboratory (LVSN), Québec, Canada.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events: Organisation

- Valérie Gouranton was Main Organizer of the Seminar "Art/Heritage/Culture" (IRISA, Rennes, February 2019), and Member of Organizing Committee of "Journée Science et Musique" (IRISA, Rennes, October 2019).
- Ronan Gaugne was Member of Organizing Committee of "Journée Science et Musique" (IRISA, Rennes, October 2019)
- Florian Nouviale was Member of Organizing Committee of the "Journée Science et Musique" (IRISA, Rennes, October 2019).

10.1.2. Scientific Events: Selection

10.1.2.1. Chair of Conference Program Committees

- Anatole Lécuyer was Member of the organization committee of IEEE VR 2019 (Panels).
- Ferran Argelaguet was Program Chair of the IEEE VR 2019 conference track.

10.1.2.2. Member of the Conference Program Committees

- Ferran Argelaguet was Member of the conference program committee of ACM SUI 2019.
- Valerie Gouranton was Member of the conference program committee of EuroVR 2019.
- Guillaume Moreau was Member of IEEE ISMAR 2019 Program committee.
- Jean-Marie Normand was Member of the program committee of IEEE VR 2019 Conference Track and of the IEEE AIVR 2019 (International Conference on Artificial Intelligence and Virtual Reality).

10.1.2.3. Reviewer

- Anatole Lécuyer was Reviewer for IEEE VRST 2019, IEEE VR 2019.
- Ferran Argelaguet was Reviewer for IEEE VR 2019, IEEE VRST 2019, ACM CHI 2019, ACM UIST 2019, IEEE ISMAR 2019.
- Maud Marchal was Reviewer for Eurographics 2019, ACM Siggraph Asia 2019, ACM UIST 2019, Eurohaptics 2019, IEEE Haptic Symposium 2019, IEEE ICRA 2019, IHM 2019.
- Valérie Gouranton was Reviewer for IEEE VR 2019, Euro VR 2019
- Guillaume Moreau was Reviewer for IEEE VR 2019, IEEE ISMAR 2019, ACM Augmented Human 2019 and IAPR Machine Vision Applications.
- Jean-Marie Normand was Reviewer for IEEE AIVR 2019, AH 2019, IEEE ISMAR 2019, IEEE VR 2019 Journal Track, IEEE VR 2019 Conference Track, IEEE CoG 2019 (Conference on Games), ACM SAP 2019.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Anatole Lécuyer is Associate Editor of the IEEE Transactions on Visualization and Computer Graphics, Frontiers in Virtual Environments, and Presence journals.

- Valérie Gouranton is Review Editor of Frontiers in Virtual Environments.
- Ferran Argelaguet is Review Editor of Frontiers in Virtual Environments.
- Maud Marchal is Review Editor of Frontiers in Virtual Environments.
- Guillaume Moreau is Review Editor of Frontiers in Virtual Environments.
- Jean-Marie Normand is Review Editor of Frontiers in Virtual Environments.

10.1.3.2. Reviewer - Reviewing Activities

- Ferran Argelaguet was Reviewer for IEEE Transactions on Visualization and Computer Graphics, IEEE Computer Graphics and Applications, International Journal on Human Computer Studies.
- Maud Marchal was Reviewer for IEEE Transactions on Visualization and Computer Graphics, IEEE Transactions on Haptics, The Visual Computer and Computers and Graphics Journal.
- Guillaume Moreau was reviewer for Computers & Graphics, IEEE Transactions on Visualization and Computer Graphics, Frontiers in Virtual Environments.
- Jean-Marie Normand was Reviewer for IEEE Transactions on Visualization and Computer Graphics, Computer Animation and Virtual Worlds.
- Ronan Gaugne was Reviewer for Thermal Science and Engineering Progress, Elsevier and Archaeological and Anthropological Sciences, Springer

10.1.4. Invited Talks

- Valérie Gouranton was invited to give a talk at Aristote Association, Ecole Polytechnique Paris (June 2019) and at Consortium 3D of TGIR HumaNum, Nantes (Dec. 2019)
- Guillaume Moreau was invited to give invited talks at University of South Australia, at the Research workshop of Ecole Centrale Group and at IRT b<>com.
- Ronan Gaugne was invited to give a talk at the EVA (Electronic information, the Visual Arts and beyond) conference “L’original et la copie”, at Musée du Quai Branly, Paris, in October 2019.

10.1.5. Leadership within the Scientific Community

- Anatole Lécuyer is Member of the Scientific Board of INCR ("Institut des Neurosciences Cliniques de Rennes")
- Ronan Gaugne is Member of the Selection and Validation Committee for the French cluster “Pôle Images et Réseaux”, and of the Consortium 3D of TGIR HumaNum.
- Valérie Gouranton is Member of the Executive Committee of AFRV (French Association for Virtual Reality), and of the Consortium 3D of TGIR HumaNum.
- Maud Marchal is Member of the Executive Committee of Eurographics French Chapter.
- Guillaume Moreau is Member of the Steering Committee of IEEE ISMAR Conference.

10.1.6. Scientific Expertise

- Ferran Argelaguet was Member of a selection committee for the ANR.
- Guillaume Moreau is Member of ANSES (National Health Agency) Working Group on the “sanitary effects of Virtual, Mixed and Augmented Reality”. He is also Member of the HCERES (Higher Education and Research Evaluation Council) Committee of SIGMA Engineering School.

10.1.7. Research Administration

- Bruno Arnaldi is Deputy Director of IRISA, and co-Head of the Scientific Council of University of Rennes (ENS Rennes, ENSC Rennes, IEP Rennes, INSA Rennes, University Rennes 1, and University Rennes 2).
- Maud Marchal is Co-Head of the Master of “Research in Computer Science” (SIF) at University Rennes 1.

- Valérie Gouranton is Head of cross-cutting Axis “Art, Heritage & Culture” at IRISA UMR 6074 and she is a member of the Conseil National des Universités 27th section (computer science).
- Guillaume Moreau is Dean of Studies at ECN.
- Jean-Marie Normand is Head of the “Virtual Reality” major at ECN.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Anatole Lécuyer:

Master AI: “Haptic Interaction and Brain-Computer Interfaces”, 6h, M2, Ecole Polytechnique, FR

Master MNRV: “Haptic Interaction”, 9h, M2, ENSAM, Laval, FR

Master SIBM: “Haptic and Brain-Computer Interfaces”, 4.5h, M2, University of Rennes 1, FR

Master CN: “Haptic Interaction and Brain-Computer Interfaces”, 9h, M1 and M2, University of Rennes 2, FR

Master SIF: “Pseudo-Haptics and Brain-Computer Interfaces”, 6h, M2, University of Rennes 1, FR

Bruno Arnaldi:

Master INSA Rennes: “VRI: Virtual Reality and Multi-Sensory Interaction Course”, 4h, M2, INSA Rennes, FR

Master INSA Rennes: “CG: Computer Graphics”, 12h, M2, INSA Rennes, FR

Master INSA Rennes: “Virtual Reality”, courses 6h, projects 16h, M1 and M2, INSA Rennes, FR

Master INSA Rennes: Projects on “Virtual Reality”, 20h, M1, INSA Rennes, FR

Ferran Argelaguet:

Master STS Informatique: “Techniques d’Interaction Avancées”, 26h, M2, ISTIC, University of Rennes 1, FR

Master SIF: “Virtual Reality and Multi-Sensory Interaction”, 8h, M2, University of Rennes 1, FR

Master SIF: “Data Mining and Visualization”, 2h, M2, University of Rennes 1, FR

Maud Marchal:

Master of Research in Computer Science: “Haptic rendering and physically-based simulation”, 4h, M2, University of Rennes 1, FR

Master INSA Rennes: “Computer Graphics”, 26h, M1 and responsible of this lecture, INSA Rennes, FR

Valérie Gouranton:

Licence: “Introduction to Virtual Reality”, 22h, L2 and responsible of this lecture, INSA Rennes, FR

Licence: Project on “Virtual Reality”, 16h, L3 and responsible of this lecture, INSA Rennes, FR

Master INSA Rennes: “Virtual Reality”, 16h, M2, INSA Rennes, FR

Master INSA Rennes: Projects on “Virtual Reality”, 20h, M1, INSA Rennes, FR

Master CN: “Virtual Reality”, 3h, M1, University of Rennes 2, FR

Ronan Gaugne:

INSA Rennes: Projects on “Virtual Reality”, 24h, L3, Insa Rennes, FR

Master Digital Creation: “Virtual Reality”, 6h, M1, University of Rennes 2, FR

Guillaume Moreau:

Dean of studies, Ecole Centrale de Nantes, FR

Virtual Reality Major, “C++ Programming for VR”, 30h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Fundamentals of Virtual Reality”, 6h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Computer Graphics”, 4h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Advanced Software Development”, 20h, M1/M2, Ecole Centrale de Nantes, FR

Computer Science Major, “Discrete Mathematics”, 10h, M1/M2, Ecole Centrale de Nantes, FR

Jean-Marie Normand:

Virtual Reality Major, “Computer Graphics”, 24h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Fundamentals of Virtual Reality”, 14h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Computer Vision and Augmented Reality”, 26h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Advanced Concepts”, 24h, M1/M2, Ecole Centrale de Nantes, FR

Virtual Reality Major, “Projects on Virtual Reality”, 20h, M1/M2, Ecole Centrale de Nantes, FR

10.2.2. Supervision

- PhD: Hakim Si-Mohammed, “Design and Study of Interactive Systems based on Brain Computer Interfaces and Augmented Reality”, INSA de Rennes, Defended December 3rd, 2019, Supervised by Anatole Lécuyer, Géry Casiez (Mjolnir, Inria) and Ferran Argelaguet
- PhD in progress: Hadrien Gurnel, “Assistance robotisée d’insertion d’aiguille par comanipulation”, Started in October 2016, Supervised by Alexandre Krupa (Rainbow, Inria) and Maud Marchal
- PhD in progress: Antonin Bernardin, “Interactive physically-based simulation of dexterous manipulation for robot understanding”, Started in September 2017, Supervised by Maud Marchal and Christian Duriez (Defrost, Inria)
- PhD in progress: Xavier de Tinguy, “Haptic manipulation in virtual environments”, Started in September 2017, Supervised by Maud Marchal, Claudio Pacchierotti (Rainbow, Inria) and Anatole Lécuyer
- PhD in progress: Rebecca Fribourg, “Perception and interaction with and via avatars”, Started in September 2017, Supervised by Ferran Argelaguet, Ludovic Hoyet (Mimetic, Inria) and Anatole Lécuyer
- PhD in progress: Romain Lagneau, “Data-driven models for dexterous manipulation of robots”, Started in Septembre 2017, Supervised by Maud Marchal and Alexandre Krupa (Rainbow, Inria)
- PhD in progress: Flavien Lécuyer, “Interactive digital introspection methods for archeology”, Started in September 2017, Supervised by Valérie Gouranton, Grégor Marchand (CNRS UMR CREAAH) and Bruno Arnaldi
- PhD in progress: Guillaume Bataille, “Natural interactions with IoT using VR/AR”, Started in October 2017, Supervised by Valérie Gouranton, Danielle Pelé and Jérémy Lacoche (Orange Labs) and Bruno Arnaldi
- PhD in progress: Etienne Peillard, “Improving Perception and Interaction in Augmented Reality”, Started in October 2017, Supervised by Guillaume Moreau, Ferran Argelaguet, Anatole Lécuyer and Jean-Marie Normand
- PhD in progress: Romain Terrier, “Presence of self and others in a collaborative virtual environment”, Started in October 2017, Supervised by Valérie Gouranton, Nico Pallamin (b<>com), Cédric Bach (HDG) and Bruno Arnaldi

- PhD in progress: Mathis Fleury, “Neurofeedback based on fMRI and EEG”, Started in November 2017, Supervised by Anatole Lécuyer and Christian Barillot (Visages, Inria)
- PhD in progress: Tiffany Luong, “Affective VR: acquisition, modelling, and exploitation of affective states in virtual reality”, Started in February 2018, Supervised by Anatole Lécuyer, Marc Diverrez (b<>com), Ferran Argelaguet
- PhD in progress: Hugo Brument, “Towards user-adapted interaction techniques based on human locomotion laws for navigating in virtual environments”, Started in October 2018, Supervised by Ferran Argelaguet, Maud Marchal and Anne-Hélène Olivier (MimeTIC, Inria)
- PhD in progress: Diane Dewez, “Avatar-Based Interaction in Virtual Reality”, Started in October 2018, Supervised by Anatole Lécuyer, Ferran Argelaguet and Ludovic Hoyet (MimeTIC)
- PhD in progress: Victor Rodrigo Mercado Garcia, “Encountered-type haptics”, Started in October 2018, Supervised by Maud Marchal and Anatole Lécuyer
- PhD in progress: Guillaume Vailland, “Outdoor wheelchair assisted navigation: reality versus virtuality”, Started in November 2018, Supervised by Valérie Gouranton and Marie Babel (Rainbow, Inria)
- PhD in progress: Gwendal Fouché, “Immersive Interaction and Visualization of Temporal 3D Data”, Started in October 2019, Supervised by Ferran Argelaguet, Charles Kervrann (Serpico Team) and Emmanuelle Faure (Mosaic Team).
- PhD in progress: Adelaide Genay, “Embodiment in Augmented Reality”, Started in October 2019, Supervised by Anatole Lécuyer, Martin Hachet (Potioc, Inria)
- PhD in progress: Martin Guy, “Physiological markers for characterizing virtual embodiment”, Started in October 2019, Supervised by Guillaume Moreau, Jean-Marie Normand and Camille Jeunet (CNRS, CLEE)
- PhD in progress: Grégoire Richard, “Touching Avatars: The role of haptic feedback in virtual embodiment”, Started in October 2019, Supervised by Géry Casiez (Loki, Inria), Thomas Pietzrak (Loki, Inria), Anatole Lécuyer and Ferran Argelaguet
- PhD in progress: Sebastian Vizcay, “Dexterous Interaction in Virtual Reality using High-Density Electrotactile Feedback”, Started in November 2019, Supervised by Ferran Argelaguet, Maud Marchal and Claudio Pacchierotti (Rainbow, Inria)

10.2.3. Juries

- Anatole Lécuyer was Referee for the PhD Theses of Justine Saint-Aubert (ISIR-UPMC), Geoffrey Gorisse (ENSAM), Léa Pillette (Univ. Bordeaux), Examiner for the PhD Thesis of Mélodie Fouillen (Inserm Lyon), Grégoire Cattan (GIPSA-Lab), and Examiner for the HDR Thesis of Sinan Haliyo (ISIR-UPMC).
- Bruno Arnaldi was Referee for the PhD Theses of Rémi Lacaze-Labadie (UTC Compiègne) and Nicolas Muller (IRIT, Toulouse), external reviewer for the PhD defense of Alexandre Kabil (IMT Atlantique - Brest) and member for the PhD Defense of Hakim Si Mohammed (INSA Rennes).
- Guillaume Moreau was external reviewer for the PhD defense of Nicolas Muller (IRIT, Univ. Toulouse), Alice Guerville-Ballé (Univ. Pau), Jason Rambach (Univ. Kaiserslautern, DE), president of the committee for Thibaud Toullier (IFSTTAR, Univ. Rennes), Nam Duong Duong (IRT b<>com, Centrale-Supelec).
- Jean-Marie Normand was examiner for the PhD Thesis of Geoffrey Gorisse (ENSAM).

10.3. Popularization

10.3.1. Articles and contents

- Ouest-France: Interview of Anatole Lécuyer (October 2019)

- France Inter: Interview of Anatole Lécuyer in the broadcast "Du vent dans les synapses" (November 2019)
- France TV: Interview of Guillaume Moreau and Jean-Marie Normand in "Télématin"

10.3.2. Interventions

- “Technoférence Humain Augmenté”: Presentation from Rebecca Fribourg (Nantes, January 2019)
- “Made by DV-Group”: Event organized by Rennes Metropole about “VR and Cinema”, presentations and demos from Ferran Argelaguet (Rennes, February 2019)
- “Laval Virtual 2019”: Demos of FIVE/SEVEN software (March 2019)
- “Journées Nationales de l’Archéologie”: Demos made by Ronan Gaugne and Valérie Gouranton (Champs Libres, Rennes, June 2019)
- “Journées Européennes du Patrimoine”: Conference and Demos made by Ronan Gaugne and Valérie Gouranton (Musée des Beaux Arts, Rennes, September 2019)
- “Festival Demain/Maintenant” : Presentation from Anatole Lécuyer (Rennes, October 2019)
- “Fête de la Science” 2019 : Presentation from Anatole Lécuyer (Saint-Louis, October 2019)
- “Journée Science et Musique” : Demos made by Florian Nouviale, Ronan Gaugne and Valérie Gouranton (Rennes, October 2019). Rebecca Fribourg and Diane Dewez also participated in the organization of the event.
- “Festival du Livre du Var” 2019 : Presentation from Anatole Lécuyer (Toulon, November 2019)
- “Digital Design Days” 2019 : Presentation from Ronan Gaugne (Milano, Italy, November 2019)

10.3.3. Internal action

- Inria/IRISA “VR Hackathon” 2019: Hackathon (20 participants) organized by Hybrid team and open to all members of Inria Rennes center (May 2019).
- “20 years of Immersia”: Event organized by Inria Rennes/IRISA center, with presentations from Anatole Lécuyer and Bruno Arnaldi, and demos made by Florian Nouviale and Ronan Gaugne (November 2019).

10.3.4. Creation of media or tools for science outreach

The ANR-FRQSC INTROSPECT project produced a transparent 3D printing of the content of an Egyptian mummy cat from a CT scan. The mummy is part of the collection of the Musée des Beaux-Arts of Rennes. The 3D printing is permanently exhibited in the Museum, next to the real mummy (Figure 21)

The immersive VR application of the LSI project developped during the hosting of the invited professor Franz Fischnaller from Albertina Accademy of Fine Arts around the Last Supper painting of Lenonardo da Vinci was deployed and exhbited in the Deep Space 8K of the Ars Electronica center in Linz, Austria (Figure 22).

11. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

[1] J.-M. BATAIL, S. BIOULAC, F. CABESTAING, C. DAUDET, D. DRAPIER, M. FOUILLEN, T. FOVET, A. HAKOUN, R. JARDRI, C. JEUNET, F. LOTTE, E. MABY, J. MATTOUT, T. MEDANI, J.-A. MICOULAUD-FRANCHI, J. MLADENOVIĆ, L. PERRONET, L. PILLETTE, T. ROS, F. VIALATTE. *EEG neurofeedback research A fertile ground for psychiatry?*, in "L’Encéphale", 2019, vol. 45, n^{o} 3, pp. 245-255 [*DOI :* 10.1016/J.ENCEP.2019.02.001], https://hal-univ-rennes1.archives-ouvertes.fr/hal-02094863

Figure 21. The mummy cat and its copy in the Museum des Beaux-Arts in Rennes.

Figure 22. The LSI project in the Ars Electronica center in Linz.

[2] M.-S. BRACQ, E. MICHINOV, B. ARNALDI, B. CAILLAUD, B. GIBAUD, V. GOURANTON, P. JANNIN. *Learning procedural skills with a virtual reality simulator An acceptability study*, in "Nurse Education Today", August 2019, vol. 79, pp. 153-160 [*DOI :* 10.1016/J.NEDT.2019.05.026], https://hal-univ-rennes1.archives-ouvertes.fr/hal-02150192

[3] A. COSTES, F. ARGELAGUET SANZ, F. DANIEAU, P. GUILLOTEL, A. LÉCUYER. *Touchy : A Visual Approach for Simulating Haptic Effects on Touchscreens*, in "Frontiers in information and communication technologies", February 2019, vol. 6, pp. 1-11 [*DOI :* 10.3389/FICT.2019.00001], https://hal.inria.fr/hal-02408724

[4] Y. GAO, Y. LIU, J.-M. NORMAND, G. MOREAU, X. GAO, Y. WANG. *A study on differences in human perception between a real and an AR scene viewed in an OST-HMD*, in "Journal of the Society for Information Display", January 2019, pp. 1-17 [*DOI :* 10.1002/JSID.752], https://hal.inria.fr/hal-01987255

[5] Y. GAO, E. PEILLARD, J.-M. NORMAND, G. MOREAU, Y. LIU, Y. WANG. *Influence of virtual objects' shadows and lighting coherence on distance perception in optical see-through augmented reality*, in "Journal of the Society for Information Display", July 2019 [*DOI :* 10.1002/JSID.832], https://hal.archives-ouvertes.fr/hal-02200576

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

[7] N. KOSMYNA, A. LÉCUYER. *A conceptual space for EEG-based brain- computer interfaces*, in "PLoS ONE", January 2019, pp. 1-30 [*DOI :* 10.1371/JOURNAL.PONE.0210145], https://hal.inria.fr/hal-02394251

[8] M. LE CHÉNÉCHAL, T. DUVAL, V. GOURANTON, J. ROYAN, B. ARNALDI. *Help! I Need a Remote Guide in my Mixed Reality Collaborative Environment*, in "Frontiers in Robotics and AI", 2019, pp. 1-25, forthcoming [*DOI :* 10.3389/FROBT.2019.00106], https://hal.archives-ouvertes.fr/hal-02314193

[9] C. LOMBART, E. MILLAN, J.-M. NORMAND, A. VERHULST, B. LABBÉ-PINLON, G. MOREAU. *Consumer perceptions and purchase behavior toward imperfect fruits and vegetables in an immersive virtual reality grocery store*, in "Journal of Retailing and Consumer Services", May 2019, vol. 48, pp. 28-40 [*DOI :* 10.1016/J.JRETCONSER.2019.01.010], https://hal.archives-ouvertes.fr/hal-01995916

International Conferences with Proceedings

[10] N. BAZOGE, R. GAUGNE, F. NOUVIALE, V. GOURANTON, B. BOSSIS. *Expressive potentials of motion capture in the Vis Insita musical performance*, in "NIME 2019 - The International Conference on New Interfaces for Musical Expression", Porto Alegre, Brazil, June 2019, pp. 1-5, https://hal.archives-ouvertes.fr/hal-02297397

[11] H. BRUMENT, R. FRIBOURG, G. GALLAGHER, T. M. HOWARD, F. LÉCUYER, T. LUONG, V. MERCADO, E. PEILLARD, X. DE TINGUY, M. MARCHAL. *Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, March 2019, pp. 1409-1410 [*DOI :* 10.1109/VR.2019.8797848], https://hal.inria.fr/hal-02284129

[12] H. BRUMENT, I. PODKOSOVA, H. KAUFMANN, A.-H. OLIVIER, F. ARGELAGUET SANZ. *Virtual vs. Physical Navigation in VR: Study of Gaze and Body Segments Temporal Reorientation Behaviour*, in "VR

2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, March 2019, pp. 680-689 [*DOI :* 10.1109/VR.2019.8797721], https://hal.inria.fr/hal-02058365

[13] S. BUTET, G. LIOI, M. FLEURY, A. LÉCUYER, C. BARILLOT, I. BONAN. *A multi-target motor imagery training using EEG-fMRI Neurofeedback: an exploratory study on stroke*, in "OHBM 2019- Orgaization for Human Brain Mapping", Rome, Italy, June 2019, pp. 1-4, https://hal.inria.fr/hal-02265496

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

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

[16] D. DEWEZ, R. FRIBOURG, F. ARGELAGUET SANZ, L. HOYET, D. MESTRE, M. SLATER, A. LÉCUYER. *Influence of Personality Traits and Body Awareness on the Sense of Embodiment in Virtual Reality*, in "ISMAR 2019 - 18th IEEE International Symposium on Mixed and Augmented Reality", Beijin, China, October 2019, pp. 1-12, https://hal.inria.fr/hal-02385783

[17] Q. GALVANE, I.-S. LIN, F. ARGELAGUET SANZ, T.-Y. LI, M. CHRISTIE. *VR as a Content Creation Tool for Movie Previsualisation*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, France, IEEE, March 2019, pp. 303-311 [*DOI :* 10.1109/VR.2019.8798181], https://hal.inria.fr/hal-02295309

[18] *Best Paper*
R. GAUGNE, T. NICOLAS, Q. PETIT, M. OTSUKI, V. GOURANTON. *Evaluation of a Mixed Reality based Method for Archaeological Excavation Support*, in "ICAT-EGVE 2019 - International Conference on Artificial Reality and Telexistence - Eurographics Symposium on Virtual Environments", Tokyo, Japan, September 2019, pp. 1-8, https://hal.inria.fr/hal-02272910.

[19] R. GAUGNE, Q. PETIT, J.-B. BARREAU, V. GOURANTON. *Interactive and Immersive Tools for Point Clouds in Archaeology*, in "ICAT-EGVE 2019 - International Conference on Artificial Reality and Telexistence - Eurographics Symposium on Virtual Environments", Tokyo, Japan, September 2019, pp. 1-8, https://hal.inria.fr/hal-02272912

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

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

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

[23] *Best Paper*
J. LACOCHE, T. DUVAL, B. ARNALDI, E. MAISEL, J. ROYAN. *Machine Learning Based Interaction Technique Selection For 3D User Interfaces*, in "EuroVR 2019 - 16th EuroVR International Conference", Tallinn, Estonia, Springer, October 2019, pp. 33-51 [*DOI :* 10.1007/978-3-030-31908-3_3], https://hal.archives-ouvertes.fr/hal-02292434.

[24] J. LACOCHE, T. DUVAL, B. ARNALDI, E. MAISEL, J. ROYAN. *3DPlasticToolkit: Plasticity for 3D User Interfaces*, in "EuroVR 2019 - 16th EuroVR International Conference", Tallinn, Estonia, Springer, October 2019, vol. 11883, pp. 62-83 [*DOI :* 10.1007/978-3-030-31908-3_5], https://hal.archives-ouvertes.fr/hal-02292436

[25] G. LIOI, S. BUTET, M. FLEURY, C. CURY, E. BANNIER, A. LÉCUYER, I. BONAN, C. BARILLOT. *Bimodal EEG-fMRI Neurofeedback for upper motor limb rehabilitation: a pilot study on chronic patients*, in "rtFIN 2019 - Real Time Functional Imaging and Neurofeedback", Maastricht, Netherlands, December 2019, pp. 1-2, https://hal.inria.fr/hal-02383532

[26] T. LUONG, N. MARTIN, F. ARGELAGUET SANZ, A. LÉCUYER. *Studying the Mental Effort in Virtual Versus Real Environments*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, France, IEEE, March 2019, pp. 809-816 [*DOI :* 10.1109/VR.2019.8798029], https://hal.inria.fr/hal-02295331

[27] F. LÉCUYER, V. GOURANTON, A. REUZEAU, R. GAUGNE, B. ARNALDI. *Authoring AR Interaction by AR*, in "ICAT-EGVE 2019 - International Conference on Artificial Reality and Telexistence - Eurographics Symposium on Virtual Environments", Tokyo, Japan, September 2019, pp. 1-8, https://hal.inria.fr/hal-02272930

[28] F. LÉCUYER, V. GOURANTON, A. REUZEAU, R. GAUGNE, B. ARNALDI. *Create by doing - Action sequencing in VR*, in "CGI 2019 - Computer Graphics International", Calgary, Canada, Springer, 2019, pp. 329-335 [*DOI :* 10.1007/978-3-030-22514-8_27], https://hal.archives-ouvertes.fr/hal-02119288

[29] M.-A. PARADIS, T. NICOLAS, R. GAUGNE, J.-B. BARREAU, R. AUGER, V. GOURANTON. *Making virtual archeology great again (without scientific compromise)*, in "CIPA 2019 - 27th CIPA International Symposium - Documenting the Past for a Better Future", Ávila, Spain, D. GONZALEZ-AGUILERA, F. REMONDINO, I. TOSCHI, P. RODRIGUEZ-GONZALVEZ, E. STATHOPOULOU (editors), International Society for Photogrammetry and Remote Sensing, 2019, vol. 42, n^{o} 2/W15, pp. 879-886 [*DOI :* 10.5194/ISPRS-ARCHIVES-XLII-2-W15-879-2019], https://hal-univ-rennes1.archives-ouvertes.fr/hal-02310425

[30] E. PEILLARD, F. ARGELAGUET SANZ, J.-M. NORMAND, A. LÉCUYER, G. MOREAU. *Studying Exocentric Distance Perception in Optical See-Through Augmented Reality*, in "ISMAR 2019 - 18th IEEE International Symposium on Mixed and Augmented Reality", Beijing, China, October 2019, pp. 1-8, https://hal.archives-ouvertes.fr/hal-02200822

[31] *Best Paper*
E. PEILLARD, T. THEBAUD, J.-M. NORMAND, F. ARGELAGUET SANZ, G. MOREAU, A. LÉCUYER. *Virtual Objects Look Farther on the Sides: The Anisotropy of Distance Perception in Virtual Reality*, in "VR 2019 - 26th IEEE Conference on Virtual Reality and 3D User Interfaces", Osaka, Japan, IEEE, March 2019, pp. 227-236 [*DOI :* 10.1109/VR.2019.8797826], https://hal.archives-ouvertes.fr/hal-02084069.

[32] H. SI-MOHAMMED, G. CASIEZ, F. ARGELAGUET SANZ, N. ROUSSEL, A. LÉCUYER. *Defining Brain-Computer Interfaces: A Human-Computer Interaction Perspective*, in "GBCIC 2019 - 8th Graz Brain-Computer Interface Conference", Graz, Austria, September 2019, pp. 1-4, https://hal.inria.fr/hal-02163771

[33] R. TERRIER, N. MARTIN, J. LACOCHE, V. GOURANTON, B. ARNALDI. *Am I better in VR with a real audience?*, in "CGI 2019 - Computer Graphics International", Calgary, Canada, Springer, June 2019, pp. 28-39 [*DOI :* 10.1007/978-3-030-22514-8_3], https://hal.archives-ouvertes.fr/hal-02119308

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

National Conferences with Proceedings

[35] R. GAUGNE, V. GOURANTON. *3D pour l'archéologie : quelles interactions, pour quoi faire ?*, in "2019 - Archéologie : imagerie numérique et 3D", Rennes, France, INRAP (editor), Séminaire scientifique et technique de l'Inrap, Sylvie Eusèbe and Théophane Nicolas and Valérie Gouranton and Ronan Gaugne, May 2019, vol. 3, https://sstinrap.hypotheses.org/1429 [*DOI :* 10.34692/XVYT-HR49], https://hal-inrap.archives-ouvertes.fr/hal-02121567

Conferences without Proceedings

[36] A. BERNARDIN, C. DURIEZ, M. MARCHAL. *An Interactive Physically-based Model for Active Suction Phenomenon Simulation*, in "SWS19 - SOFA Week Symposium", Paris, France, November 2019, https://hal.inria.fr/hal-02419381

[37] L. DEVIGNE, M. BABEL, R. LE BRETON, E. LEBLONG, V. GOURANTON, F. PASTEAU, B. FRAUDET, S. GUEGAN, G. VAILLAND, Y. GAFFARY. *Expérience de conduite en fauteuil roulant dans une ville virtuelle avec un simulateur multisensoriel conçu selon une approche centrée sur l'utilisateur : une étude de cas*, in "SOFMER 2019 - 34ème congrès de la Société Français de Médecine Physique et de Réadaptation", Bordeaux, France, October 2019, https://hal.inria.fr/hal-02339573

[38] M. FLEURY, G. LIOI, C. BARILLOT, A. LÉCUYER. *The use of haptic feedback in Brain-Computer Interfaces and Neurofeedback*, in "CORTICO 2019 - COllectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur", Lille, France, March 2019, https://hal.archives-ouvertes.fr/hal-02387408

[39] M. FLEURY, G. LIOI, C. BARILLOT, A. LÉCUYER. *The use of haptic feedback in Brain-Computer Interfaces and Neurofeedback*, in "rtFIN 2019 - Real Time Functional Imaging and Neurofeedback", Maastricht, Netherlands, December 2019, https://hal.archives-ouvertes.fr/hal-02387400

[40] S. LE FRANC, M. FLEURY, M. COGNÉ, S. BUTET, C. BARILLOT, A. LÉCUYER, I. BONAN. *Influence of visual feedback on the illusion of movement induced by tendon vibration of wrist in healthy subjects*, in "SOFMER 2019 - 34ème congrès de la Société Français de Médecine Physique et de Réadaptation", Bordeaux, France, October 2019, https://hal.inria.fr/hal-02415992

[41] G. LIOI, S. BUTET, M. FLEURY, A. LÉCUYER, I. BONAN, C. BARILLOT. *Efficacy of EEG-fMRI Neurofeedback in stroke in relation to the DTI structural damage: a pilot study*, in "OHBM 2019 - 25th Annual Meeting of the Organization for Human Brain Mapping", Rome, Italy, June 2019, pp. 1-4, https://hal.inria.fr/hal-02265495

Scientific Books (or Scientific Book chapters)

[42] J.-B. BARREAU, E. LANOË, R. GAUGNE. *3D Sketching of the Fortified Entrance of the Citadel of Aleppo from a Few Sightseeing Photos*, in "Digital Cultural Heritage", H. KREMERS (editor), Springer International Publishing, June 2020, pp. 359-371, First Online : 22 June 2019 [*DOI :* 10.1007/978-3-030-15200-0_24], https://hal-univ-rennes1.archives-ouvertes.fr/hal-02164770

Other Publications

[43] M.-S. BRACQ, E. MICHINOV, B. ARNALDI, A. AUDINOT, B. CAILLAUD, B. GIBAUD, V. GOURANTON, P.-L. HENAUX, A. LAMERCERIE, B. NOGUES, P. JANNIN. *Modeling, Simulation and Training Procedural Skills: User experience and acceptability of a virtual reality simulator for scrub nurses in neurosurgery*, January 2019, vol. 36, 1 p. , 19th International Meeting on Simulation in Healthcare (IMSH), Poster, https://hal.archives-ouvertes.fr/hal-02123682

References in notes

[44] D. A. BOWMAN, E. KRUIJFF, J. J. LAVIOLA, I. POUPYREV. *3D User Interfaces: Theory and Practice*, Addison Wesley, 2004

[45] A. LÉCUYER. *Simulating Haptic Feedback Using Vision: A Survey of Research and Applications of Pseudo-Haptic Feedback*, in "Presence: Teleoperators and Virtual Environments", January 2009, vol. 18, n° 1, pp. 39–53, http://www.mitpressjournals.org/doi/abs/10.1162/pres.18.1.39