Maintaining Physical Collaboration in Virtual Reality

Applicant: Wen-Jie Tseng (Technical University of Darmstadt)
Host laboratory: Sorbonne Université (ISIR) with Gilles Bailly (Sorbonne Université, CNRS)
Collaborations with: Anatole Lécuyer (Inria), Gery Casiez (Univ. Lille)
[redacted]

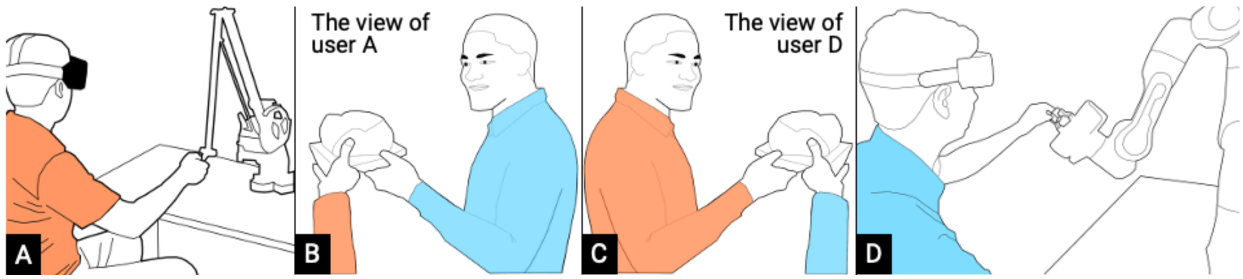


Figure 1: Two persons (A and D) are in different physical spaces but collaborate in the same virtual environment through their corresponding avatars (B and C). Particularly, A and D manipulate shared 3D objects with rich haptic feedback during the collaborative task. Each physical space has different properties in geometry (e.g., size, configuration) and haptic interface (haptic device for A and robot arm for D). The intelligent system should favor physical collaboration despite heterogeneous setups.

1. Context: Virtual Reality (VR) allows people to remotely collaborate in the same virtual environment, where users are represented by avatars and interact with virtual objects using controllers. However, controllers only provide limited haptic feedback—an essential sensory modality for social interaction [12], enhancing immersive experiences [7], or physical tasks [10]. Our core research question is: How do we enable haptic feedback and physical interaction for VR collaboration between users in separate physical spaces? Precisely, **how can an intelligent system support synchronous physical interaction between two VR users in separate physical spaces with potentially different geometry and haptic interfaces?**

2. Objective: This proposal aims to enable physical interaction in remote VR collaboration. The objective is to investigate how an intelligent system empowers local and remote users to physically co-manipulate shared 3D objects. We envision four contributions:

A) An adaptation model to dynamically modify the VR scene (visual representation) and robot configuration (haptic feedback) to reduce visuo-haptic inconsistencies and in turn favoring physical collaboration and embodiment. The adaptation model has to determine at each time step the best compromise between (1) maintaining visual consistency between the local and remote users to favor a high level of synchrony between users' actions and (2) maintaining locally visuo-haptic consistency so that what the local user sees is coherent with what she feels (haptic feedback). The model is further described in Fig. 2.

B) A demonstrator illustrating a set of interaction techniques allowing two remote users to physically collaborate with a high level of synchrony.
C) Empirical findings of how relevant variables, such as, robot latency, network latency, visuo-haptic inconsistencies, or task difficulty) affect human performance, decision-making and the sense of embodiment.
D) Deriving research guidelines for designing intelligent systems favoring physical collaboration in VR.

3. Previous Work: Previous research in the 2000s [2, 6, 9] has investigated haptic human-human communication in remote setups, focusing on performance and the sense of collaboration. However, the investigated haptic interfaces are limited regarding interaction and applications. For instance, the Phantom forces users to interact with a handle. In contrast, recent research on haptic interfaces now provides rich physical interaction in VR with robotic arm [1], robotic column [3], or redirecting hand movements to a passive prop [11]. These interfaces break the constraint of desktop interaction, allowing people to walk in a large arena and directly "touch" virtual objects (they do not force users to interact with an instrument). While recent works offer new opportunities for remote human-human communication, they have been primarily designed and evaluated in the single-user context. We want to exploit these technologies to revisit human-human communication and address the challenges of co-manipulating shared objects between local and remote users in VR.

We will primarily focus on embodiment (sensing the body as one's own, being able to control it, and being in the environment [5]), as previous work shows that enriched haptic feedback can enhance embodiment in VR [8]. We will consider human decision-making [13] and how performing assisted co-manipulation in VR influences human decision-making at different levels, from the choice of movements on the manipulated object to high-level decision making such as trust in the remote user or/and attitudes towards a specific topic [15, 16, 17].

4. Approach: We aim to extend physical interaction in VR from the single-user to multi-user scenario in two different physical spaces. Both local and remote spaces contain a haptic interface, like a robotic arm [1], robotic column [3], or hand redirection [11]. However, the local and remote spaces can differ in geometry, size and haptic interface characteristics and the communication between the local and remote spaces can be deteriorated (e.g., delay) [4]. The complexity of the setup requires intelligent systems who (1) understand users intentions, (2) control the position and the forces of the haptic devices and (3) adapts the visual feedback to ensure a high degree of visuo-haptic consistency. Precisely, this setup raises several research questions and engineering challenges:

- What is the influence of constrained setups (e.g., diversity of devices, latency) on the sense of embodiment, collaboration, but also on human decision-making? We plan to conduct experiments to understand the relationships between these variables.

- How to coordinate visual and haptic feedback locally and remotely to favor physical collaboration and embodiment ? We plan to develop an intelligent system (Fig. 2) that dynamically chooses and parametrizes techniques (namely visuo-haptic illusions) to maintain a high level of visuo-haptic consistency.

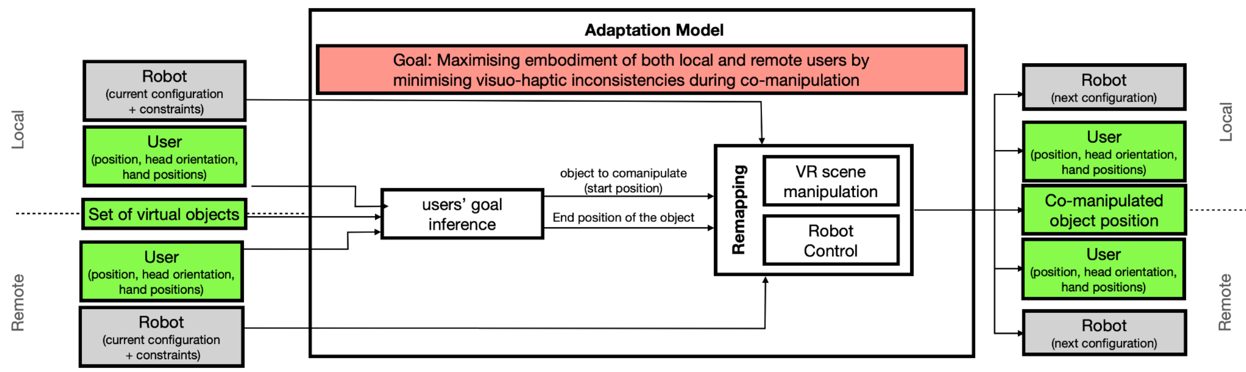


Figure 2: Overview of the adaptation model. The inputs of the model are the (1) **VR scene** represented by the avatar of the local and remote users and a set of virtual objects that can be co-manipulated and (2) **physical robots** (local and remote) used to provide haptic feedback. Depending on the user movements, the model updates the visual elements of the **VR scene** and the configuration of the **robots** to (1) maintain visuo-haptic consistency locally and (2) a high-level of synchrony between the local and remote VR scene.

Inferencing the users' goal. The model should first infer which object the users want to co-manipulate so that the physical prop (attached to the robots) can overlay the corresponding virtual object. The inference is based on the positions of the users and their head orientations. We will build on the algorithm of Bouzbib et al. [3].

The model should also determine where the users want to move the object. The algorithm of Bouzbib et al. [3] needs to be updated as the head orientation information is likely to be less informative. For instance, users can look at the target position, but also the co-manipulated object or the user avatar for confirmation.

Remapping. Given the output of the users' inference goal, the model should determine how to move the robots and the virtual elements of the scenes. Several visuo-haptic illusions have been proposed in the literature to ensure that the haptic feedback is aligned with visual feedback. We will build on these illusions to develop the remapping component. The challenge will be to transpose them from a static environment to a highly dynamic environment.

In practice, the problem can be formulated as an **optimisation problem** where (1) the **objective function** to minimise is current and future local and remote "visuo-haptic consistencies", (2) the **problem space** is the set of visuo-haptic illusions and their corresponding parameters and (3) the **constraints** are the characteristics of the robots and the VR scene.

5. Research plan: Our proposal follows the sub-goals (SGs):

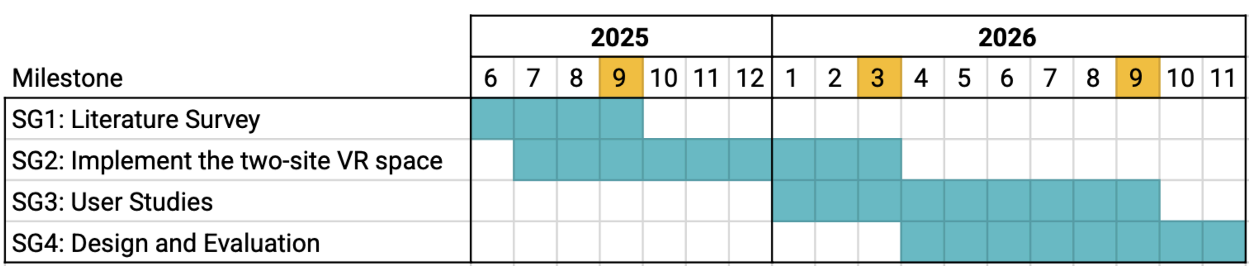
SG1 - Survey - Understanding the design space of collaborative physical tasks in VR
Based on existing literature, we aim to systematically survey the design space of collaborative physical tasks in real and virtual environments as well as how to support interaction with different haptic solutions, especially in human-human communication.

SG2 - Implementation - Develop the setup for remote VR collaboration
We will develop a two-site VR space with haptic interfaces and an intelligent system to support a subset of the scenarios identified in SG1. The intelligent system that can decide which technique is the most appropriate depending on the setup and users (see Figure 2). During this stage, we will also address engineering challenges, such as time delay while people interact remotely in two sites.

SG3 - User Studies - Exploring remote collaborative tasks in constrained setups
The outcome of SG2 allows us to investigate the impact of latency, visuo-haptic inconsistencies, and task difficulty on VR collaboration. We aim to investigate how these factors and the adaptation model affect the sense of embodiment and collaboration as well as other dependent variables to define during the project, such as human decision-making. These studies will be conducted in a controlled environment. We also aim to study how collaboration skills learned in VR with a specific setup can be transferred to the real world.

SG4 - Design & Evaluation - How to support physical interactions for remote VR collaboration?
The findings of SG3 will provide recommendations to refine the adaptation model to support the co-manipulation of shared objects between local and remote users. This sub-goal aims to further improve the implementation of our system (SG2) and evaluate it in a more ecological environment. For instance, the task is less defined and thus more uncertain about users intentions and behavior.

Planning: The proposal, spanning two years, aims to achieve SG1-4 in the following figure. The yellow blocks mark our tentative deadline (every March and September) for submitting projects to top-tier venues in the HCI/VR community, like CHI, UIST, VR, TOCHI, or IJHCS.



6. Positioning [redacted] How an intelligent system (combining a robotic device and computational models of human behavior) supports physical interaction between two humans. This proposal extends the theme 1 by aiming to favor physical embodied synchronization. It is also related to theme 3 as it is likely to observe co-adaptation phenomena (to manage) between the users and the intelligent system: the users will discover and learn the opportunity and limitations of the proposed setup and adapt accordingly. We aim to study how collaboration practices and skills learned in VR can be transferred in the real world. Our proposal is also connected to CATS as we aim to implement a two-site physical VR space consisting of heterogeneous haptic interfaces.

7. Partnership: This project will bring together partners with complementary areas of expertise from experimental design, interaction design, and computational modeling in HCI, VR, and Haptics.

Applicant: Wen-Jie Tseng (Technical University of Darmstadt) is a PhD student working on understanding embodiment and spatial cognition of humans in VR. He has a strong background in empirical methods (VR ‘24, CHI ‘22) and interaction design (CHI ‘23, UIST ‘19, UIST ‘18). The PhD defense will be in March 2025.

Host: Dr. Gilles Bailly (Sorbonne Université, CNRS, ISIR) has a strong background in robotics technologies and intelligent systems for HCI as well as computational models of human behavior. The ISIR lab is especially appropriate to host this project with the CoVR platform including an engineer (Clement Alberge).

Collaborators: Dr. Anatole Lécuyer (Inria, Rennes) has strong background in virtual reality technologies and haptics and will participate remotely to the co-supervision of the work with complementary expertise. Inria Rennes research center can welcome the postdoc for visits, and give access to its large visuo-haptic platform (Immersia CAVE-like room, augmented with force-feedback devices).

Dr. Géry Casiez (Univ. Lille) has strong background in interaction techniques and haptics and will participate remotely to the co-supervision of the work with complementary expertise. Univ. Lille can welcome the postdoc for visits.

8. References:

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