Augmenting Holographic Telepresence with Mobile Robots for Tangible Remote Collaboration in Mixed Reality

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Abstract

In the context of diversifying workstyles and infectious disease countermeasures, remote collaboration and communication are becoming increasingly important. To support this, much research in telepresence, which conveys the presence of users in remote locations, has been conducted. Additionally, telepresence systems utilizing devices such as robots and pin displays have been proposed to enable physical embodiment and interactions. However, these are often expensive and offer limited interactions. Therefore, I propose a concept of telepresence using a collective of robots. As a first step towards this, I introduce a telepresence system for remote collaboration using holographic avatars and mobile robots, named HoloBots. With HoloBots, remote users can not only be visually and spatially present but also physically interact with local users and their environment. HoloBots employs Azure Kinect to capture the remote user's body in real-time and displays it through Hololens2. The remote user's movements are synchronized with a tabletop mobile robot (Sony Toio) placed in front of the local user. Moreover, I explore the design space of HoloBots, such as the actuation of objects, sharing of tangible UIs, interactions with miniature bodies, and communication using haptics. Furthermore, I present future directions for telepresence using a collective of robots.

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Chapter 1

Introduction

In the context of infectious disease prevention and the diversification of work styles, remote collaboration and communication have become increasingly crucial. Numerous studies have been conducted to support remote work, one of which involves the technology of telepresence, designed to convey a sense of presence in remote locations. A key aspect within this domain is the ability to engage in physical interactions, as if one were actually present and working alongside others. This has been addressed by technologies like robotic telepresence and physical telepresence, which focus on enabling physical body representations and physical interactions. However, these technologies face challenges due to their limited range of possible representations and interactions and the complexity of the configurations. To address these challenges, I have proposed the concept of telepresence using a collective of robots. As the first step in this direction, I have developed a system named HoloBots.

1.1 Telepresence

Telepresence refers to technology that provides a person in a remote location with the sensation of being in the same place. This technology facilitates remote collaboration and enhances remote communication. Research in telepresence has mainly focused on visual representation, with various systems being proposed in response to changes in the media used. For instance, 2D video conferencing tools (like Microsoft Teams [1] and Zoom [2]) have been proposed for PCs and 3D avatar-based tools (such as VRChat [3]) for Virtual Reality (VR) devices. Moreover, in Mixed Reality (MR), in which users can interact with virtual objects in the real world, holographic telepresence technologies such as Holoportation [OERF+16] have emerged, displaying full-body captures of remote individuals for realistic avatar representation. Research has also been conducted to augment telepresence by integrating physical representations and interactions into these visual representations. This advancement enables remote individuals to interact with physical objects or local users and to have a physical presence themselves.

[1] `https://www.microsoft.com/en-us/microsoft-teams/group-chat-software`
[2] `https://zoom.us/`
[3] `https://hello.vrchat.com//`

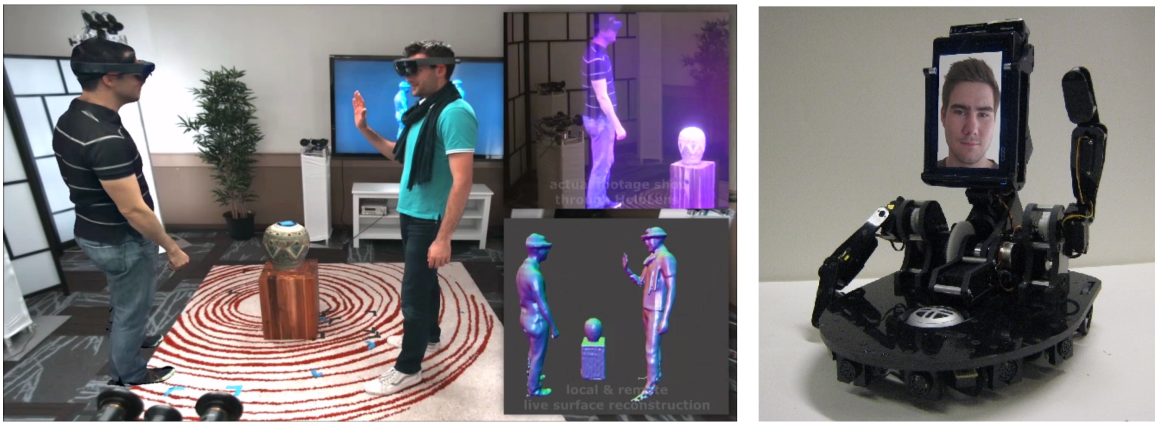

Figure 1.1: Telepresence in Mixed Reality [OERF+16] (left) and robotic telepresence [AB10] (right).

1.2 Robotic Telepresence

In the context of Human-Robot Interaction (HRI), telepresence utilizing robots has been proposed. In the robotic telepresence system, remote individuals are represented as robots, such as humanoid robots and robots with a 2D video screen. These robots convey gestures and movements to local users, creating a sense of the remote individual's presence. Moreover, robots can manipulate objects in remote locations, enabling collaborative interaction with physical items. However, humanoid robots have some drawbacks. They are often expensive and have limited expressiveness. The conveyance of gestures and facial expressions of the robot is significantly influenced by the number and quality of motors used.

1.3 Tangible Bits to Physical Telepresence

1.3.1 Tangible Bits and Radical Atoms

In the field of Human-Computer Interaction (HCI), the concept of *Physical Telepresence* has emerged, rooted in the concept of Tangible Bits [IU97] introduced in 1997. This concept aimed to bridge the gap between the physical and virtual worlds. Tangible Bits proposed interfaces where manipulating physical objects could control bits, and observing physical objects could reveal the state of bits. This approach features high affordance and body engagement. For instance, in the Tangible User Interface, tangible interaction with data is possible, providing explicit affordance—understanding how to use it. In *musicBottles* [Ish99], opening and closing a bottle controls music playback. Similarly, in *Megereality* using a dropper symbolizes absorbing and releasing information [WBS20]. Tangible User Interfaces (TUI) are also characterized by high body engagement, meaning they involve physical interaction with information, which is beneficial for memory and creativity enhancement. Furthermore, in 2012, the concept of Radical Atoms was introduced.

Unlike previous TUIs where physical objects were static and merely manipulated, Radical Atoms [ILBL12] allowed objects to transform and move, enabling tactile presentations. Though virtual objects themselves are intangible, aligning physical objects with virtual counterparts can provide tactile feedback. This can be achieved using pin displays (e.g., *inForm* [FLO+13]) or mobile robots to create shapes (e.g., *ShapeBots* [SZK+19]), enhancing haptic communication. Additionally, objects can be moved, making virtual UIs interactive, as seen in systems like *exTouch* [KNHI13].

1.3.2 Physical Telepresence

Within the currents of this research, the concept of *Physical Telepresence* emerged, which enables remote users to physically interact with local users through an actuated environment. *Physical Telepresence* embodies the characteristics of Tangible Bits and Radical Atoms. It allows local users to engage with a high body engagement, while remote users can experience haptic feedback and manipulate physical objects. For example, using a pin display system like *inForm* [FLO+13], which pushes objects up from below, a remote user can roll a ball or lift a book. This enables local users to receive tactile feedback and collaborate with high body engagement. However, this setup is complex. Even simple operations, such as rolling a ball, require intricate maneuvers, like lifting the ball and then gradually shifting it sideways. Furthermore, increasing the resolution poses significant challenges. Doubling the resolution would require twice the number of pins, making the system increasingly expensive.

Figure 1.2: Physical Telepresence [LFOI14]

1.4 Telepresence Using a Collective of Robots

To address the challenges posed by the complexity, cost, and limited interaction capabilities of existing telepresence systems that enable physical interaction, I propose a concept of telepresence using a collective of robots. Collectives of robots have been widely utilized in the HCI field, leading to the development of various interfaces. These collectives have included small robots, shape-changing robots, and drones. For instance, collectives of small robots have been used for visualizing information (e.g., *Zooids* [LGKP+16], *Ubiswarm* [KF17]) and providing haptic notifications (e.g., *Swarm Haptics* [KF19]). Collectives of shape-changing robots have been applied in VR for haptic feedback (e.g., *HapticBots* [SOS+21]) and object actuation (e.g., *ShapeBots* [SZK+19]). Additionally, collectives of drones have been employed for 3D information visualization (e.g., *Flying LEGO bricks* [RBT+20]) and as three-dimensional input/output interfaces (e.g., *GridDrones* [BRMV18]). Thus, the use of robot collectives has enabled a broader range of interactions compared to shape-changing interfaces such as pin displays.

From this perspective, implementing a telepresence system with robot collectives could create systems capable of diverse interactions at a low cost. In this concept, robot collectives, previously utilized for information visualization and object actuation, are repurposed for body representation of remote users and enabling remote object manipulation (Fig. 1.3). Using a collective of robots at appropriate times and for suitable purposes, a wide range of applications could be accommodated. Moreover, rather than constructing everything out of robots, strategically placing them only where necessary — in body parts that need representation and locations where interaction occurs — can achieve significant effects with few robots.

As an initial step of this concept, I propose HoloBots [IFI+23], a telepresence system using mobile robots and holographic avatars captured with RGBD cameras and displayed on MR devices. I have extensively explored the range of possible interactions, including object actuation, virtual hand physicalization, world-in-miniature exploration, shared tangible interfaces, embodied guidance, and haptic communication with this system. Utilizing these interactions, I have proposed applications that leverage these interactions.

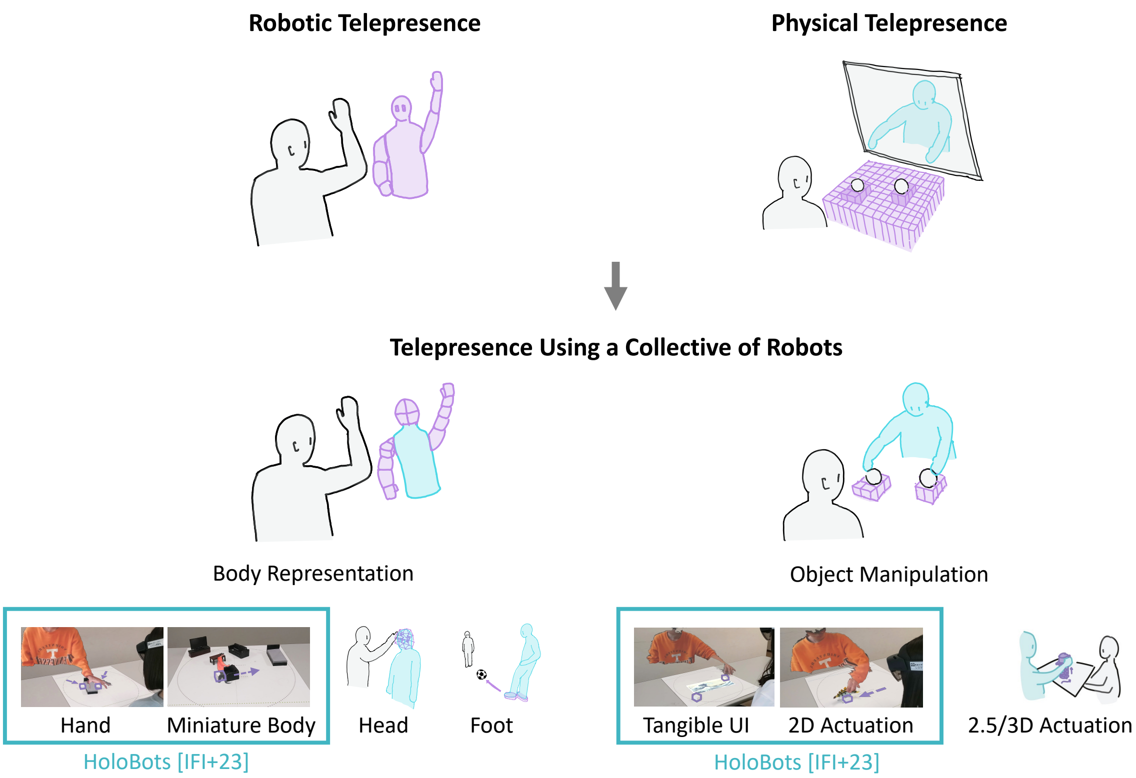

Figure 1.3: Telepresence Using a Collective of Robots

1.5 Contribution

The contributions of this thesis are as follows:

1. Creating the telepresence system, HoloBots, that augments holographic telepresence with multiple tabletop mobile robots that enables scalable, deployable, and generalizable tangible remote collaboration.
2. A design space exploration and application demonstrations that showcase a set of possible interactions and use cases enabled by HoloBots.
3. Results and insights from our user study that confirm the benefits of our approach over hologram-only and robots-only conditions.

1.6 Collective Research Efforts

While I primarily led this project, it was conducted as a collaborative project with multiple researchers from the University of Tsukuba and the University of Calgary. Therefore, in the descriptions that follow, the term 'we' is predominantly used to reflect this collaborative effort.

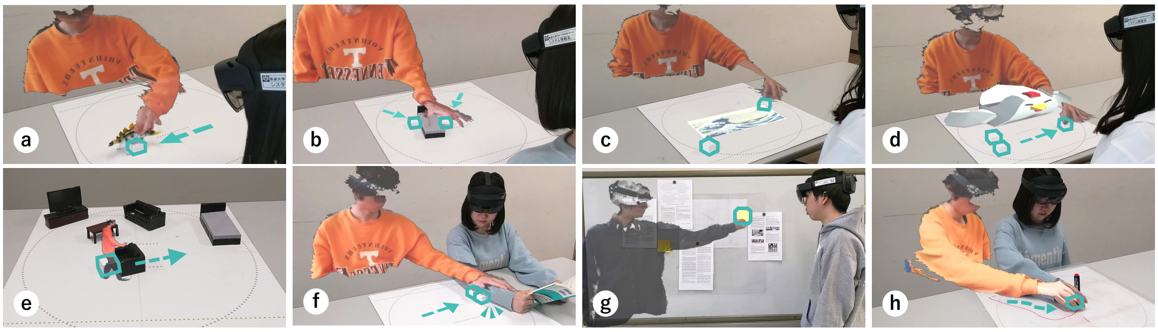

Figure 1.4: HoloBots explores augmenting holographic telepresence with tabletop mobile robots for remote collaboration. The remote user can interact with the local user through various methods, such as (a, b) actuating objects, (c, d) sharing tangible user interfaces, (e) representing the body, and (f) providing haptic feedback. By using attachments, HoloBots is adaptable in situations that involve (g) vertical surface and (h) drawing scenarios.

Chapter 2

Related Work

In this chapter, we first discuss prior research in remote collaboration and the challenges associated with it. Then, we address studies related to the approach we use to tackle these challenges, specifically focusing on bi-directional virtual-physical interaction and tangible user interfaces, and articulate the differences between these existing methodologies and our approach.

2.1 Remote Collaboration

2.1.1 Mixed Reality Remote Collaboration

Recent advances in mixed reality technologies have enabled immersive remote collaboration that was not possible with traditional desktop interfaces. Prior research has explored various approaches for immersive telepresence, such as holographic teleportation (e.g., *Holoportation* [OERF+16], *Virtual Makerspaces* [RJS21], *Loki* [TKAF+19]), virtual avatars (e.g., *CollaboVR* [HDP20], *Mini-Me* [PLH+18], *Shoulder of Giant* [PLI+19], *ARTEMIS* [GJS+21]), and projected video stream (e.g., *Room2Room* [PKB+16], *3D-Board* [ZRIH14]). These systems allow remote users to be spatially co-located in the same shared space, which greatly enhances collaborative experiences [BSYB20, CQW+20]. For example, by showing virtual hands and bodies in 3D space, the local users can more easily understand the intention of the remote users for various physical tasks such as block assembly [ZBZ+22], origami [KLH+19, KLBH20], mechanical tasks [OTS+21, OYN+21], and physiotherapy education [FKS23]. However, current holographic telepresence lacks the physical embodiment of the remote user, which significantly reduces the sense of co-presence [LNB+18]. This limitation also constraints rich physical affordances which we naturally employ in co-located physical collaboration [LFOI14, SYP+18]. To address this issue, we integrated mobile robots with holographic avatars to enable the physical embodiment of remote users.

2.1.2 Robotic Telepresence

In the context of remote collaboration, several prior studies have addressed this issue, one of which is robotic telepresence. Robotic telepresence aims to physically embody remote users by adding a robotic body to a 2D video screen (e.g., *MeBot* [AB10], *RemoteCode* [SRAG22]) or by replicating the remote user with a humanoid or non-humanoid robot (e.g., *TELESAR V* [FFK+12], *Te-*

lenoid [ONK+11], *You as a Puppet* [SMK+17], *GestureMan* [KOY+00], *Geminoid* [SKO+07]). The robotic telepresence can greatly enhance user engagement by enabling physical interactions such as gestures [AB10] and body movement [NKI11, RMT14, LT11]. For example, mobile robots allow remote users to move freely around a table to interact with local users and objects for remote education (e.g., *RobotAR* [VLZ+21], *ASTEROIDS* [LSL+22]). Beyond a screen-based representation, *VROOM* [JZWR20, JZWR21] overlays a holographic avatar on a telepresence robot that enriches non-verbal communication such as gestures or eye-contact. However, while these studies enable the embodiment of remote users, they often struggle with facilitating collaborative object manipulation alongside remote participants. Additionally, the possible body representations they can achieve are limited.

2.1.3 Physical Telepresence

An alternative approach to adding physical embodiment to remote users is using *synchronized distributed physical objects* [BID98], rather than embodying users themselves with robotic telepresence. Such an approach was originally explored through *InTouch* [BD97], *ComTouch* [COJ+02], and *PsyBench* [BID98], in which synchronized tangible tokens embody the remote user's motion and behavior. This idea has evolved into a concept of *physical telepresence* [LFOI14], which synchronizes physical shape rendering with the remote users' visual appearance. For instance, Leithinger et al. [LFOI14] uses a shape-changing display [FLO+13] to physically render a remote user's hand and surrounding objects with screen-based visual feedback. Recent works have also expanded this concept by combining a virtual avatar with a motorized X-Y plotter to actuate a single token (e.g., *Physical-Virtual Table* [LNB+18]). However, the existing approach using shape displays lacks deployability due to the dedicated hardware requirement, and X-Y plotters lack scalability and generalizability due to a single point actuation and limited interaction area. More closely related to our work, a few researchers have explored the use of mobile robots for tangible remote collaboration in VR (e.g., *PhyShare* [HZP17]) and mixed reality environments (e.g., *Siu et al.* [SYP+18]). However, this approach of using multiple mobile robots has not been fully explored yet, as these prior works do not present the comprehensive design space and have not conducted any user evaluation to understand the benefits and limitations of this approach. Beyond these prior works, we contribute to 1) an exploration of the broader design space with a demonstration of comprehensive applications, and 2) a holistic user evaluation through condition experiments.

2.2 Bi-Directional Virtual-Physical Interaction

Outside the context of remote collaboration, past HCI research has also explored bi-directional virtual-physical interaction by leveraging augmented reality and actuated environments [SKX+22]. For example, systems like *Kobito* [AMI+05], *Augmented Coliseum* [KSN+06], and *IncreTable* [LHY+08] explore the synchronous coupling between AR and actuated physical objects, which can enrich visual feedback and affordances of robots and actuated tangible interfaces. These interfaces typically employ robot motion (e.g., *exTouch* [KNHI13]), actuated tangible tokens (e.g., *PICO* [PI07], *Reactile* [SKGY18], *Actuated Workbench* [PMAI02]), IoT devices (e.g., *MechARSpace* [ZLW+22], *WIKA* [JKYN20], *Kim et al.* [KBH+18]) to synchronize between virtual and physical outputs in a bi-directional manner. Similar to our work, *Sketched Reality* [KMF+22] and *Physica* [LSN23] explores bi-directional interaction between embedded virtual objects and tabletop robots. Our system extends their work in the context of holographic tangible remote collaboration in mixed reality environments.

2.3 Actuated Tangible User Interfaces

Actuated tangible user interfaces were originally developed to address the challenge of digital-physical discrepancies in conventional tangible interfaces [PNO07]. Towards this goal, HCI researchers have explored a variety of actuated tangible user interfaces [PNO07] and shape-changing user interfaces [RPPH12,CZ11,ARS+18], using magnetic actuation [PI07], ultrasonic waves [MCAS12], magnetic levitation [LPI11], and wheeled and vibrating robots [NLH+13]. Rosenfeld et al. [RZSP04] introduced the concept of using physical mobile robots as an actuated tangible user interface. This concept has been expanded through various systems, such as *Zooids* [LGKP+16], *Shape-Bots* [SZK+19], *HERMITS* [NLT+20], *Rolling Pixels* [LKK20], and *(Dis) Appearables* [NTZ+22]. Swarm user interfaces can also provide haptic sensations [KF19, SSGY17, SOS+21, ZKW+17] and actuate everyday objects [KDDF20, FKS22]. Inspired by these works, we also leverage multiple tabletop robots for our actuated interfaces.

2.4 Summary

There has been substantial research to support remote collaboration. A prominent challenge in this field is the inability to facilitate physical interactions. To overcome this challenge, studies have been conducted in robotic telepresence and physical telepresence. However, these approaches have faced issues, such as limited body representations and possible interactions, and the complexity of the systems that have been used. We address these challenges by utilizing mobile robots that synchronize with holographic avatars. This solution enables a variety of body representations and bi-directional tangible interaction.

Chapter 3

HoloBots: System Design

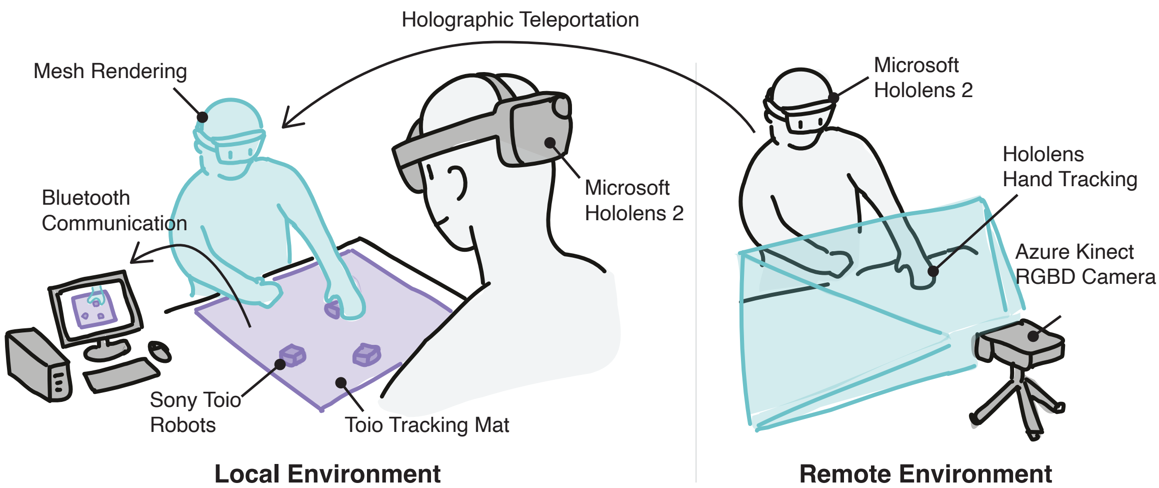

Figure 3.1: System Setup: The local user can see the remote user's avatar and interact with Toios or virtual objects with the remote user through Hololens. The remote user's body is tracked by Azure Kinect, and the hands are tracked by Hololens.

This section introduces HoloBots, a system that augments holographic telepresence with multiple tabletop robots. As illustrated in Figure 3.1, HoloBots consists of three main components: 1) *capturing a remote user* with the Azure Kinect depth camera, 2) *holographic rendering and hand tracking* with Microsoft Hololens 2 headset, and 3) *synchronized actuation* with Sony Toio tabletop mobile robots.

3.1 Capturing a Remote User with a Depth Camera

The Azure Kinect RGB-D camera is used to capture the remote user's body. The camera is positioned in front of the remote user with a tripod stand. The Kinect camera is connected to the local PC

(G-Tune, Intel Core i7-11800H 2.30GHz CPU, NVIDIA GeForce RTX 3060 GPU, 64GB RAM) via a USB cable. The depth information is captured through the Azure Kinect Sensor SDK running on the local PC. The depth sensor first generates a point cloud with a resolution of 640 x 576, which is then converted into a real-time colored 3D mesh using the Azure Kinect Examples for Unity package [1]. Mesh data is captured with 30 FPS, and the size of each mesh data is approximately 20 MB.

3.2 Holographic Rendering and Hand Tracking

In our setup, both local and remote users wear the Microsoft Hololens 2 mixed reality headset, which has a diagonal field of view of 52 degrees. The remote user's holographic mesh generated by the local PC is rendered in Hololens 2 through Holographic Remoting [2], enabling high-quality and low-latency (60 FPS) rendering over an Ethernet connection, allowing the local user to view the mesh. Hololens 2 is also used to track the user's hand movements using the MRTK hand-tracking library. Tracked hands are used to 1) grab virtual robots to manipulate and synchronize the physical one in the remote environment, or 2) move robots based on the finger position to physicalize the virtual hand. These processes are executed on Unity running on the remote PC (G-Tune, Intel Core i7-11800H 2.30GHz CPU, NVIDIA GeForce RTX 3070 GPU, 64GB RAM) and the local PC, respectively, connected with Hololens 2 through Holographic Remoting.

3.3 Synchronized Actuation with Tabletop Mobile Robots

Our system uses Sony Toio [3] as tabletop mobile robots. Each robot measures 3.2 cm × 3.2 cm × 2.5 cm and can move at a speed of up to 35 cm/sec for straight-line movement and 1500 deg/sec for rotation. The robot has a built-in camera that can scan patterns printed on a mat (Toio Tracking Mat) to detect their position and orientation. The size of the tracking mat has 55 cm × 55 cm of covered area, but it can be extended by aligning multiple mats. Each Toio robot is controlled using the Toio SDK for Unity [4] on a PC and continuously sends its position and orientation to the PC via Bluetooth® standard Ver. 4.2 every 10 ms. For the controlling algorithm, we adapt to the open-source library [NLT+20] and rewrite the algorithm for our Unity application. To start using our application, the local user first performs a manual calibration to align the remote user's holographic mesh with the Toio mat. This alignment can be bypassed in subsequent uses, saving the relative position between the Toio mat and the avatar mesh. By placing a QR code on the Toio mat to acquire the mat's position and leveraging the relative position, we can display the avatar mesh in the appropriate position (Fig. 3.2). After the calibration, each robot's position is controlled through the following three ways: 1) physical Toio movement in the remote environment, 2) virtual object movement in the remote user's Hololens, or 3) finger position movement of the remote user. When both users have a physical Toio setup, the system can simply synchronize the position of

[1] `https://assetstore.unity.com/packages/tools/149700`

[2] `https://learn.microsoft.com/en-us/windows/mixed-reality/develop/native/holographic-remoting-player`

[3] `https://www.sony.com/en/SonyInfo/design/stories/toio/`

[4] `https://github.com/morikatron/toio-sdk-for-unity`

each environment. On the other hand, when only the local user is equipped with the Toio robot, then the remote user can manipulate virtual Toios by grasping and manipulating virtual Toio objects rendered in the Hololens, while the local user manipulates physical Toios. Alternatively, the remote user can manipulate these Toio robots with hand and finger tracking. For the finger binding, we use the thumb, index, and/or pinky finger positions, depending on the available number of robots The position data for each robot is sent between the remote and local PCs through UDP communication. In our implementation, we set the Toio robot's speed up to 17.5 cm/sec, taking into account the balance between speed and accuracy. Therefore, if the remote user attempts to move the local Toio robot at a speed higher than this, it may lead to positional errors. Considering the tradeoff between precise movements and jittering, we set the default tolerance to 1.1 cm for all interactions, except for the miniature body interaction, where we set it to 0.4 cm since accuracy with the avatar' s body was more crucial than some small jittering. Finally, to increase the reproducibility, we make our software open source [5].

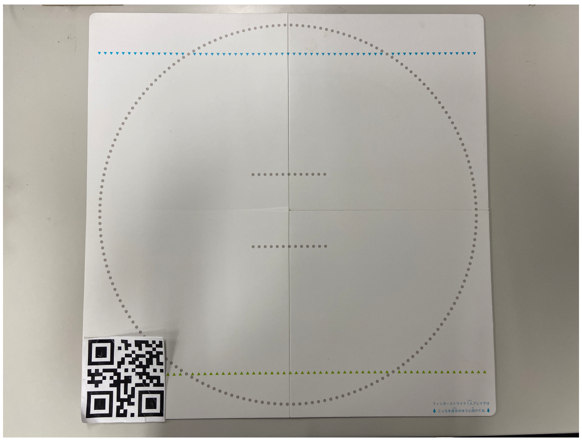

Figure 3.2: QR code placed on the Toio mat.

[5] https://github.com/KeiichiIhara/HoloBots

Chapter 4

HoloBots Design Space

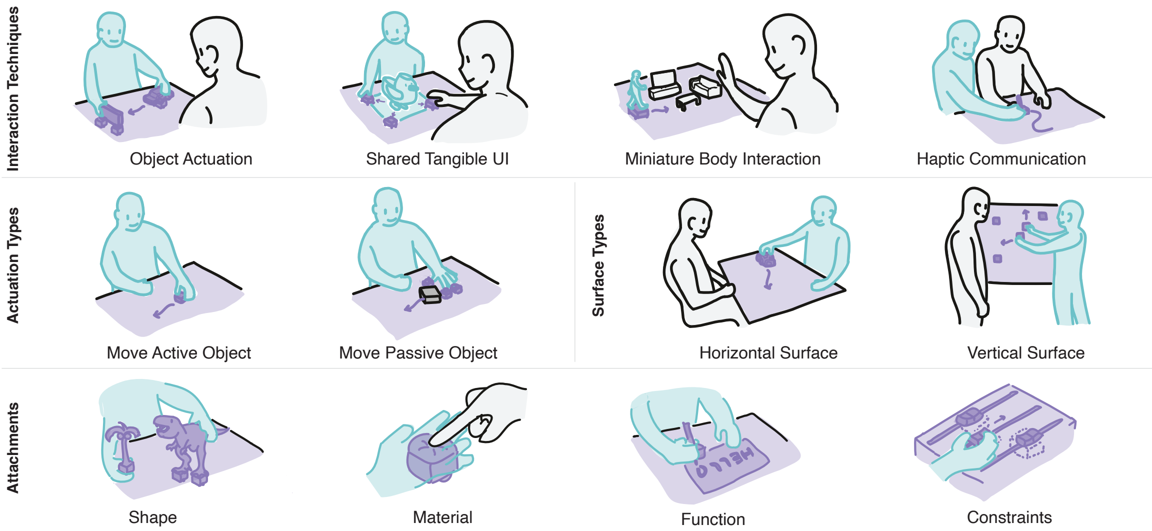

Figure 4.1: Design Space of HoloBots.

In this section, we explore the design space of HoloBots in the following four dimensions: 1) interaction techniques, 2) actuation types, 3) surface types, and 4) physical attachment (Figure 4.1).

4.1 Interaction Techniques

There are four patterns that can be considered as methods for remote users to interact with local users: Object Actuation, Share TangibleUI, Miniature Body Interaction, Haptic Communication.

Object Actuation

HoloBots offers various ways for remote users to interact with the local user. The object actuation enables remote users to move and manipulate objects in the local environment. For example, remote users can directly grab the Toio robot to move its location, or the attached object for more expressive engagement.

Figure 4.2: Storytelling

The object actuation can be used for different use cases, such as storytelling, gaming, and drawing. For storytelling, HoloBots allows both local and remote users to participate in creating a story together with tangible objects. The local user can either observe as an audience member or actively engage with the story-creation process. Figure 4.2 illustrates a remote user physically moving a dinosaur toy on a stage to narrate a story to the local user. This provides, for example, engaging tangible storytelling for children and their remote parents or friends.

Shared Tangible UI

Another interaction technique is the shared tangible user interface, which allows both local and remote users to manipulate virtual object properties through tangible tokens. Toio robots can be represented as various tangible UI elements, such as control points, buttons, sliders, and knobs, so that by controlling the same UI, local and remote users can manipulate the UI together. For example, Figure 4.3 illustrates users changing the position and scale of the virtual picture by manipulating robots, which are represented as a control point of the image.

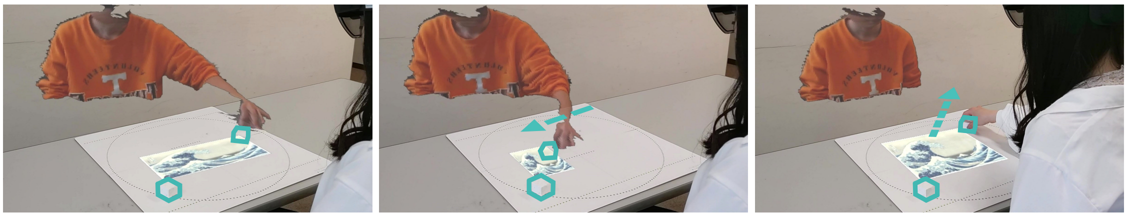

Figure 4.3: Shared Tangible UI

In Figure 4.4, three Toios are used as a tangible UI for manipulating a 3D object. Two of the Toios represent sliders and adjust the width and depth of the object, while the third Toio represents a knob and alters the object's height.

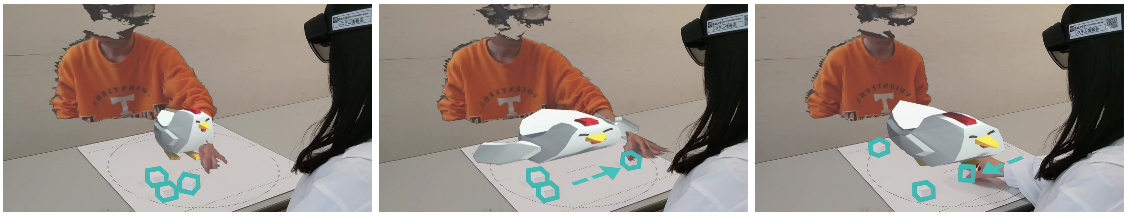

Figure 4.4: Collaborative Design

Miniature Body Interaction

The robot can also embody the remote user through a miniature body. Our system also facilitates the collaborative world-in-miniature exploration, by representing as the miniature user. Similar to the prior work that explores tangible world-in-miniature exploration (e.g., *miniStudio* [KKN16], *Does it Feel Real?* [MRD+19], *Shoulder of Giants* [PLI+19], *ASTEROIDS* [LSL+22]), the tangible embodiment of the miniature user facilitates rich physical affordances for the world-in-miniature interaction, while providing effective visual feedback through holographic representation. The remote user can walk around on a real-size environment, which is captured and tracked through Azure Kinect body tracking. For example, the remote user can visually instruct the local user using gestures and physically move objects in the local environment by pushing them with Toios (Figure 4.5).

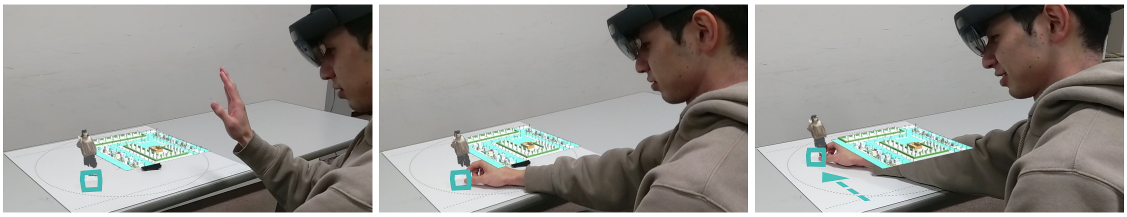

Figure 4.5: Miniature Body Interaction

Taking inspiration from the immersive interior and architectural design (e.g., *DollhouseVR* [ISS+15]), this could be used for the collaborative world-in-miniature exploration, in which the robot can embody the physical representation of the miniature user. For example, Figure 4.6 illustrates an application for collaborative interior design. This application uses miniature furniture to facilitate discussion and decision-making between remote and local users. The remote user is visually represented as a miniature avatar, with a Toio representing the remote user's physical body. The remote user can visually instruct the local user using gestures and physically push the miniature furniture to arrange the position.

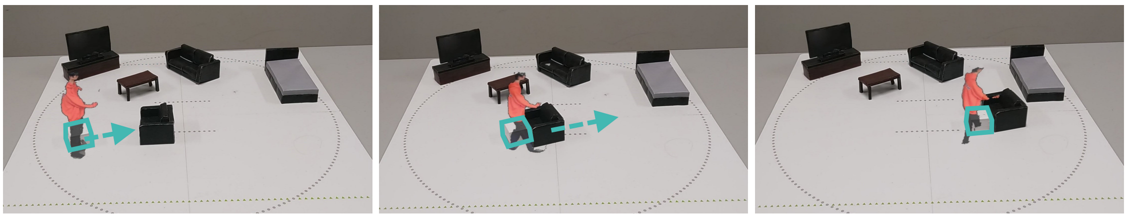

Figure 4.6: Interior Design

Haptic Communication

Haptic communication is another interaction technique that enables the remote user to provide haptic feedback to the local user. There are various ways to provide haptic communication. For example, the user can guide the Toio robot to navigate the remote user based on the actuation, similar to *dePend* [YK13], as if they were holding their hands. This technique can be used for hands-on instruction. Alternatively, the remote user can physically touch the local user by moving and touching the local user's body using Toios, similar to *SwarmHaptics* [KF19]. This can be used for remote social interaction.

Figure 4.7 shows a remote user controlling the movement of a red pen to draw on the physical canvas. By attaching a physical pen to a Toio, the remote user can move the pen and draw on a physical canvas. Local and remote users can therefore collaborate in real-time to create drawings and illustrations together.

Figure 4.7: Haptic Communication

This can also provide haptic notifications, enabling remote users to physically notify local users using Toios. By attaching Toios to the remote avatar's hand, the remote user can touch the local user and initiate communication. In Figure 4.8, the remote user touches the local user who is reading a book to start a conversation.

Figure 4.8: Notification

4.2 Actuation Types

Move Active Object

In HoloBots, the remote users can actuate physical objects in two ways. First, the user can simply grasp and move the Toio robot itself. By moving the Toio, which is attached to the various object, HoloBots enables the remote user to actuate physical objects (Figure 4.2).

One possible application is the remote gaming experience. By attaching Toios to game objects, the local user can physically interact with the remote user through the tangible game. Figure 4.9 depicts a table hockey game application that utilizes three Toios—two for the mallets and one for the puck, similar to [NTZ+22, KMF+22]. This application allows users to play and compete with each other in real-time, creating an engaging and immersive gaming experience.

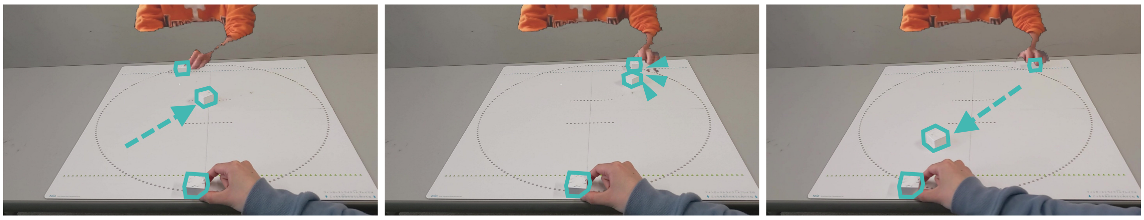

Figure 4.9: Table Hockey

Move Passive Object

Alternatively, the user can also actuate everyday passive objects by pushing these objects with the Toio. This allows actuating objects without attaching robots in advance. Similar to [KMPC23], by making the robots follow the user's fingers, the remote user can physicalize their hands and fingers, so that pushing the other passive objects (Figure 4.10). This method allows an intuitive way of interacting with physical objects, as the remote user can use hand gestures to control objects. In the current setup, each Toio can push an object up to 32 grams.

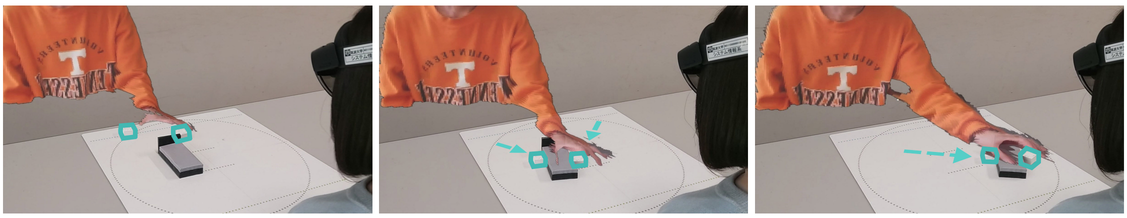

Figure 4.10: Move Passive Object

4.3 Surface Types

Horizontal Surface

HoloBots also supports two different surface types that the robot can move around. The first one is the horizontal surface, such as a tabletop surface where the users sit down together to manipulate objects on the table.

Vertical Surface

Alternatively, by attaching a small magnet at the back of the Toio, Toio can move on a vertical surface such as a whiteboard or a magnetic wall. By moving Toios on a vertical surface can be useful for applications that require standing up, such as brainstorming or presentations. In our prototype, we attach an N35 neodymium magnet (8 mm $\times$ 3 mm, 1 mm thickness) to the bottom of the Toio robot with tape, which has a strong attraction force to be attached to the whiteboard, while weak enough to move on a wall. For the tracking of the vertical surface, we use a thinner tracking mat (Toio Developer Mat, 0.1 mm thickness) that can be attached to the whiteboard. With the vertical surface, we can also expand the application domains, such as collaborative discussion and brainstorming with the post-it notes on a whiteboard (Figure 4.11).

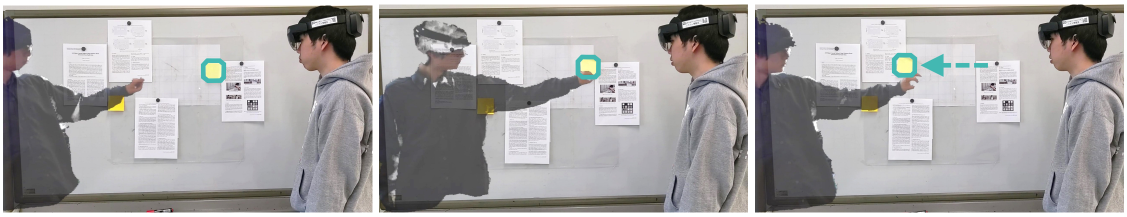

Figure 4.11: Vertical Surface

4.4 Attachments of the Robot

HoloBots is also designed to be versatile and adaptable to various applications by allowing the user to attach different components to the robot. These attachments provide additional functionalities and enable the robot to perform a wider range of tasks, making it suitable for a variety of applications.

Shape Props

Shape props can modify the robot's shape and physical appearance. As illustrated in Figure 4.2, attaching a dinosaur toy to the robot can be used to represent a dinosaur, expanding its interactive potential. By attaching Toios to physical objects such as puppets, stuffed animals, toy figures, and LEGO blocks, both local and remote users can move the objects, crafting the story and narrative, as we do in physical space.

Material Props

The addition of material props such as soft materials, fur, and fabric enables the local user to enhance the sensation of remote objects and users. For example, by attaching soft materials, mobile robots can represent remote users' hands to improve haptic communication. Also, the use of fabric materials enables the mobile robots to represent portions of the remote user's arm that are clothed.

Functional Props

Attachments can supplement the robot with added functionalities. For example, Figure 4.12 illustrates remote users drawing on a transparent sheet using a robot equipped with a pen, which facilitates visual communication between users. As shown in Figure 4.11, attaching post-it notes to the mobile robots enables the remote user to highlight specific parts in the local user's environment. Also, by attaching magnets to the robots, users can extend their mobility from horizontal to vertical surfaces.

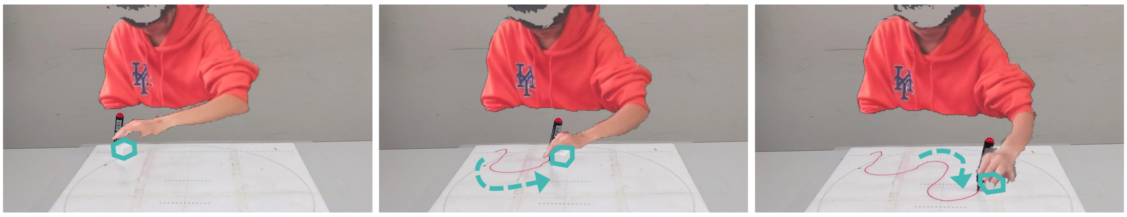

Figure 4.12: Pen Attachment for Drawing

Constraints

Mechanical constraints, such as rings and rubber bands, can be employed to restrict the movements of mobile robots as PICO [PI07]. This provides both the remote and local users to move the robots within a specific range of movement. For example, by using a straight ring, the movement of mobile robots can be limited to a straight line, which could help the creation of a precise slider UI. Also, confining all the mobile robots within a ring can help limit the area in which the remote user can influence the local environment.

Chapter 5

User Study

To evaluate the effectiveness of incorporating both virtual and physical representations in holographic remote collaboration, we conducted a user study comparing our system with Hologram-Only and Robots-Only conditions across four distinct interactions. We gathered both quantitative and qualitative measurements for various aspects, such as social presence, system usability, and cognitive workload, with a within-subject user study.

5.1 Method

5.1.1 Participants

We recruited 12 participants (11 male, 1 female) from our local university, with an age range of 21-24 years (M = 22.1, SD = 1.16). Participants were surveyed on their familiarity with VR/AR using a 7-point Likert scale from 1 (novice) to 7 (expert), and the average score was 2.75 (SD = 1.71).

5.1.2 Study Setup

We present the setup used in our study in Figure 5.1. One of the authors acts as a remote collaborator (referred to as "the experimenter") for each participant to reduce differences in interaction between groups. The participant and the experimenter are situated in separate rooms and communicate remotely. The dimensions of the participant's room were approximately 11.3 m by 5.2 m, while the experimenter's room measured approximately 7.5 m by 5.9 m. Both the participant and experimenter were equipped with Hololens 2 headsets. On the participant's desk, we placed the Toios and a Toio mat. To enable the experimenter to view the participant's workspace, we used an iPad to capture the video image and transmitted it to the experimenter's display (Fig. 5.2).

For audio communication, we used Discord[1], a voice chat application. To mitigate any potential interference from the Toio's sound, the participant wore noise-canceling headphones (Sony WH-1000XM4).

[1]https://discord.com/

Figure 5.1: Study Setup. Left: Experimenter's room, Right: Participant's room

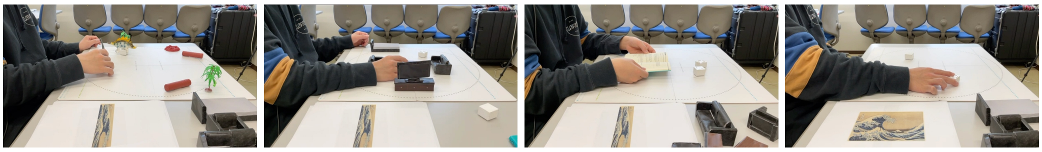

Figure 5.2: Appearance of the participant's environment captured on an iPad.

5.1.3 Study Design

We designed our study with a within-subject design that compares the following three conditions:

C1. Hologram + Robots : Participants interacted with the remote experimenter via hologram and voice chat with using mobile robots.

C2. Hologram-Only : Participants interacted with the remote experimenter via hologram and voice chat without using mobile robots.

C3. Robots-Only : Participants interacted with the remote experimenter via voice chat without a hologram with using mobile robots. Figure 5.3 shows the appearance of the three conditions.

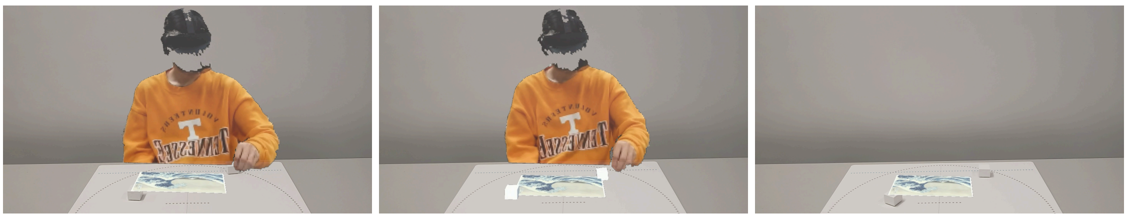

Figure 5.3: From left to right, showing the three conditions, C1, C2, and C3.

To evaluate the difference in these conditions across various interactions, we used four application scenarios that best represent each interaction technique in our design space:

D1. Object Actuation : We used the physical storytelling application (Figure 4.2). Participants were instructed to create a short story with the remote experimenter by manipulating virtual or physical dinosaur toys. The remote experimenter could also move the dinosaur toys. The fundamental elements of the stories shared similarities, including dinosaurs fighting, making up, walking around, and talking to each other. However, participants chose how the dinosaurs fight, where they make up or rest, and which directions they walk. We displayed virtual toys for C2 and used physical toys for C1 and C3.

D2. Shared Tangible UI : We used virtual image manipulation (Figure 4.3). Participants were instructed to adjust the size of a virtual picture until it matched the target size printed on paper, collaborating with the remote experimenter. The virtual cubes or mobile robots were attached to the upper left and bottom right of the virtual picture, and participants and a remote experimenter could adjust the size by moving them. We used virtual cubes for C2, and used physical cubes for C1 and C3. The virtual picture was displayed in all conditions.

D3. Miniature Body Interaction : We used the interior and architectural design application (Figure 4.6). The remote experimenter was presented as a miniature body, similar in size to miniature furniture. Participants were instructed to move the furniture and determine furniture placement in discussion with the remote experimenter. The remote experimenter could also physically move the furniture in the conditions with a mobile robot.

D4. Haptic Communication : We used the haptic notification application (Figure 4.8). Participants were instructed to read a book and engage in conversation with the remote experimenter when they were contacted. The remote experimenter initiated contact through virtual or physical touch, with mobile robots following the remote experimenter's fingers to physically touch the participants.

5.1.4 Measurements

We measured four different aspects: 1) **Social Presence**, 2) **Cognitive Workload**, 3) **System Usability**, and 4) **Preference**. To measure Social Presence, we used the Social Presence Questionnaire [HB06]. This questionnaire consists of three sub-scales: Co-Presence (CoP), Attentional Allocation (AA), and Perceived Message Understanding (PU), comprising 18 questions in total. For measuring usability, the System Usability Scale (SUS) [Bro95] was employed. The SUS is composed of 10 items and outputs a score out of a maximum of 100 points. To assess the workload, the NASA Task Load Index (NASA-TLX) [HS88] was used. NASA-TLX evaluates six factors: mental demand, physical demand, temporal pressure, performance, effort, and frustration. Each factor is scored out of a maximum of 100 points, and weights are assigned to each factor to calculate an overall score out of 100. The actual form used is included in the appendix. Participants' preferences were also measured using a questionnaire where they indicated their most preferred condition. In addition to these measurements, we conducted an interview after the study to gather qualitative feedback from participants.

5.1.5 Procedure

After participants signed a consent form, we provided them with instructions on how to use the Hololens 2 and Toio robot. Participants then conducted a task involving 12 sessions (4 applications

$\times$ 3 conditions), each lasting 3 minutes. Participants used four applications in the following order: Shared Tangible UI, Object Actuation, Miniature Body Interaction, and Haptic Communication. Participants conducted each application in all three conditions (C1, C2, and C3). The order of the three conditions was counterbalanced across participants to control for order effects. After each application, participants answered the social presence questionnaire. After each condition, participants answered the SUS and NASA-TLX questionnaire to compare the three conditions. In total, we asked the participants to complete 12 social presence questionnaires and 3 SUS and NASA TLX questionnaires. After the participants finished all of the sessions, we conducted a brief open-ended interview for 10-15 minutes. The study took approximately 90 minutes in total, and each participant was compensated with 10 USD.

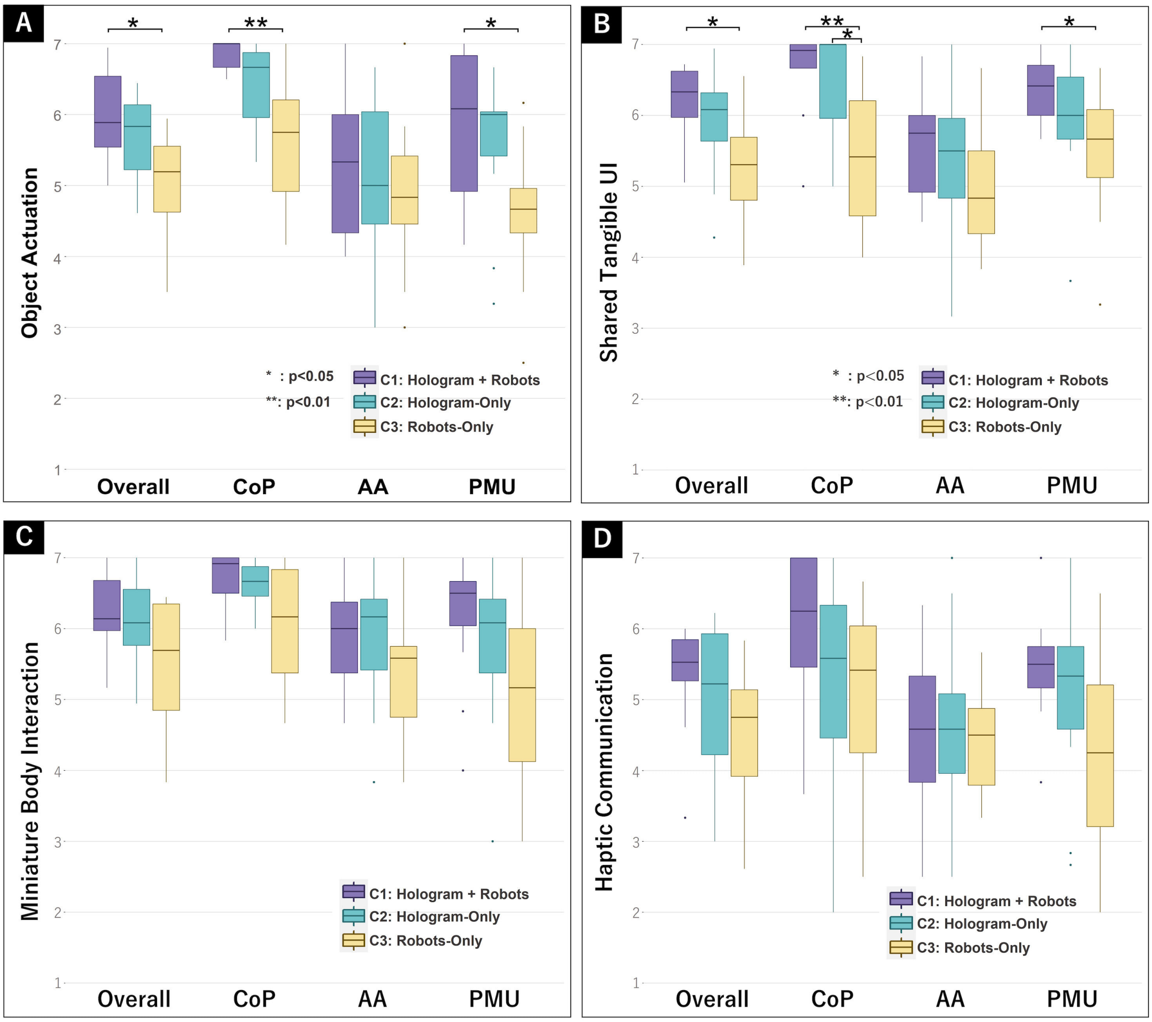

Figure 5.4: Social Presence Questionnaire Results. A: Object Actuation, B: Shared Tangible UI, C: Miniature Body Interaction, D: Haptic Communication. CoP: Co-Presence, AA: Attentional Allocation, PMU: Perceived Message Understanding.

5.2 Results

To analyze the data collected in our study, we employed a Friedman's test for each measurement. To assess pairwise differences between conditions, we conducted multiple pair-wise comparisons using the Wilcoxon signed-rank test with Bonferroni correction. We set the significant level at 5 %.

5.2.1 Social Presence

The Social Presence Questionnaire consisted of three sub-scales: Co-Presence (CoP), Attentional Allocation (AA), and Perceived Message Understanding (PU). Figure 5.4 shows the result of the social presence questionnaire for a total of 12 sessions (4 applications $\times$ 3 conditions for each). In addition, we calculated an overall score by averaging the three sub-scales. We checked the internal consistency with Cronbach's alpha for each sub-scale: $\alpha_{CoP} = 0.90$, $\alpha_{AA} = 0.78$, $\alpha_{PMU} = 0.93$.

For Object Actuation (D1) and Shared Tangible UI (D2), Hologram + Robots (C1) condition had significantly higher overall social presence scores than Robots-Only (C3) condition. For both Object Actuation (D1) and Shared Tangible UI (D2), pairwise comparisons revealed that Hologram + Robots (C1) condition was significantly higher scores than Robots-Only (C3) condition for CoP (D1: $Z = 3.68$, $p = 0.0007 < 0.001$, D2: $Z = 3.29$, $p = 0.003 < 0.01$), PMU (D1: $Z = 2.46$, $p = 0.042 < 0.05$, D2: $Z = 2.61$, $p = 0.027 < 0.05$), and Overall (D1: $Z = 2.63$, $p = 0.025 < 0.05$, D2: $Z = 2.86$, $p = 0.013 < 0.05$).

In the interviews, participants made comments that suggested that Hologram + Robots (C1) condition resulted in a stronger sense of presence compared to Hologram-Only (C2) condition. Specifically, one participant noted that *"Hologram + Robots clearly felt the presence of the other party, whereas Hologram alone was less present." (P1)*, while another participant mentioned that *"Hologram-only conditions were difficult to react to when the other person was out of sight" (P2)*. These comments suggest that combining mobile robots with holographic telepresence could help users better understand the remote user's actions and movements, even when the holographic user is out of sight. Furthermore, for all four applications, the graph of the data suggested that Hologram + Robots (C1) had the highest scores, followed by Hologram-Only (C2) and Robots-Only (C3).

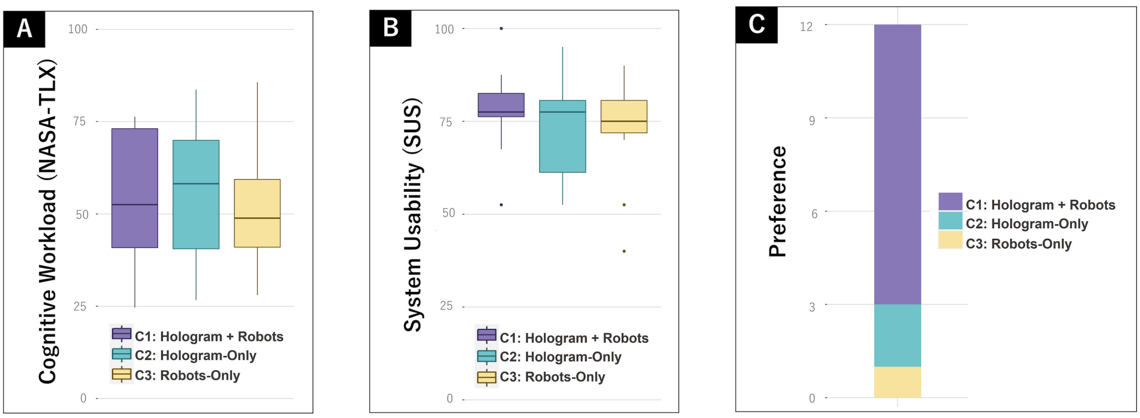

Figure 5.5: A: Cognitive Workload (NASA-TLX), B: System Usability (SUS), C: Preference

5.2.2 Cognitive Workload

The results for the cognitive workload are shown in Figure 5.5 (A). A lower score indicates a lower workload. The average score for each condition was 54.0 ($SD = 19.4$) for Hologram + Robots (C1) conditions, 55.3 ($SD = 18.9$) for Hologram-Only (C2), and 51.6 ($SD = 16.9$) for Robots-Only (C3). The Friedman test showed no significant difference ($\chi^2(2) = 0.30$, $p = 0.86$).

5.2.3 System Usability

The results for the system usability scale are shown in Figure 5.5 (B). A higher score indicates higher usability. The average score for each condition was 77.9 ($SD = 11.3$) for Hologram + Robots (C1) conditions, 73.3 ($SD = 14.2$) for Hologram-Only (C2), and 72.9 ($SD = 14.1$) for Robots-Only (C3). The Friedman test showed no significant difference ($\chi^2(2) = 1.64$, $p = 0.44$). During the interviews, participants provided feedback on the usability. One participant noted that *"Conditions which use Toio were easy to manipulate" (P3)*, and another participant noted that *"It was easy to adjust the size of the virtual picture using Toio" (P8)*. Although Hologram + Robots (C1) had a higher average usability score (77.9) than the average score (68) [Sau11], it was not significantly better than Hologram-Only (C2). One participant reported, *"The coupling between the actual movements and the robot was slow and misaligned, which sometimes make it difficult to understand" (P3)*. This feedback suggests that the low ability of coupling between the hologram and mobile robots may have negatively impacted usability.

5.2.4 Preference

The results for the preference are shown in Figure 5.5 (C). 75 % of the participants preferred Hologram + Robots (C1) as the best, followed by Hologram-Only (C2) (17 %) and Robots-Only (C3) (8 %). Chi-squared goodness of fit test revealed a significant difference from random choice ($\chi^2(2) = 9.5$, $p = 0.009 < 0.01$). In our study, participants preferred Hologram + Robots (C1) over Hologram-Only (C2) and Robots-Only (C3). Five out of nine participants mentioned social presence as a key factor in their preference for Hologram + Robots (C1), while the remaining four participants mentioned usability as a determining factor. Therefore, the high social presence and usability in Hologram + Robots (C1) can enhance the overall user experience.

5.3 Limitations and Design Implications

5.3.1 Precise Coupling between Holographic Users and Robot Movement

In the applications used in the study, the coupling between the virtual body movements and mobile robots was occasionally slow and misaligned due to the Toio's maximum speed and the calibration error between the avatar and Toios. Upon testing the start latency, the average latency was 0.483 s, 0.262 s, 0.443 s, and 0.615 s in D1, D2, D3, and D4, respectively. This issue could potentially impact both the social presence and usability of the Hologram + Robots (C1) condition. Employing faster mobile robots and implementing a more accurate position calibration method between the avatar and Toios could alleviate this problem.

5.3.2 Noise of Robot Movement

Several participants reported that the sound generated by the Toios could be distracting and interfere with their ability to concentrate on the task. For example, one participant commented *"Toios sound was sometimes a little loud, and it was difficult to concentrate on the task." (P2)*, while another mentioned *"I was distracted by the noise of Toios" (P3)*. The noise is influenced by the number of objects attached to the Toio and the number of Toios moved. Upon testing the noise levels generated when moving the Toio 45 cm in 4 seconds, the maximum recorded noise was 64.5 dB, 60.3 dB, 65.0 dB, and 70.0 dB in D1, D2, D3, and D4, respectively. This issue could potentially impact the user experience and social presence. To address this problem, we could improve the system to make Toios travel to their destination by the shortest route, reducing travel time and the duration of sound generation.

5.3.3 Bi-Directional Collaboration between Participants

Additionally, the collaboration in our study was between a participant and an experimenter. To gain further insights, it may be beneficial to set up an environment where participants can collaborate with other participants without the presence of an experimenter. This can provide insights on more realistic collaboration scenarios.

5.3.4 Group Size

In our study, collaboration was limited to only two people, one participant and one experimenter. Using larger groups could potentially increase the number of interactions and affect the social presence and user experience. However, this could also increase conflicts and misunderstandings. Therefore, conducting studies with larger groups could help us understand how these factors influence our system.

5.3.5 Number of Robots

In our study, we used two Toios, but it is possible to use more. One participant noted that *"I thought it would be good if the picture application could increase the number of manipulable objects (Toio) and allow more complex UI manipulation" (P8)*. This comment suggests that using more Toios for UI manipulation could affect usability and user experience. Additionally, we could use more Toios for body or hand representation, which could enhance the resolution of the remote user's movements and gestures, which could enhance the social presence.

5.3.6 Enhancing Holographic Visualization

In this study, we used a single Kinect camera to capture the remote user's body movements for holographic avatar generation. Future work could expand this setup by adding more Kinect cameras to capture the user's hologram from multiple angles. This could improve the remote user's clarity and accuracy via multi-directional coverage. Through these improvements, the local user would better comprehend the remote user's intentions and interactions with the physical environment and overall body language. However, the more detailed the display, the more data is generated, which may affect data processing and communication. Furthermore, as can be seen in Figure 5.3, reflections on the Hololens2 have made it difficult to capture facial images clearly. This could make it harder to convey emotions.

5.3.7 Communication Constraints

To avoid the influence of the communication environment, in this experiment, the remote user's Kinect camera was connected to the local PC via USB. However, in actual use, it is necessary to connect via the internet. Nevertheless, as the data for 60 seconds of point cloud data amounted to about 15 GB, the data size of the holographic avatar is large. Therefore, when actually using it, it is necessary to devise ways to reduce the data volume. For example, methods such as using a coarser point cloud or capturing the user in advance to reconstruct an avatar, and then transmitting only the bone information in real-time can be considered.

Chapter 6

Future Work

In HoloBots, we utilized Sony Toio, a mobile robot that moves on a mat, and synchronized its movements with a holographic avatar, exploring and implementing a comprehensive range of interactions. However, this design space depends on the form factor of the Toio robot. Therefore, by employing a collective of other types of robots, broader interactions become possible. Here, as future research, we present potential interactions along with the available robots that could be used.

6.1 Body Representation

In HoloBots, we implemented representations of hands and miniature bodies. However, by utilizing robots that move in 2.5 dimensions and drones or different tracking methods, it becomes possible to represent other parts of the body, including heads and feet, and expand the body representations conducted in HoloBots.

6.1.1 Head Representation

Since Toio robots can only move in two dimensions, they were unable to represent the head, where movement in three dimensions is crucial. However, it is possible to represent the head by using a collective of drones capable of moving in three dimensions. Attaching coverings around the drones, such as *GridDrones* [BRMV18], makes touch interactions feasible. Thus, representing the remote user's head enables the initiation of conversations by touching the remote user's head or directing the remote user's attention by changing the head's orientation.

6.1.2 Feet Representation

Since Toio can only move on a mat, it was difficult to represent movements in a larger space, making the representation of feet challenging. However, as used in *ASTEROIDS* [LSL^{+}22], by attaching QR codes to the top of the robots and tracking them from the ceiling, it becomes possible to follow the robots over a wider area. This enables interactions throughout an entire room, allowing for the tracking robots that represent the remote user's feet. This can be used in games involving the use of feet, like soccer, or to clarify the position of a remote user.

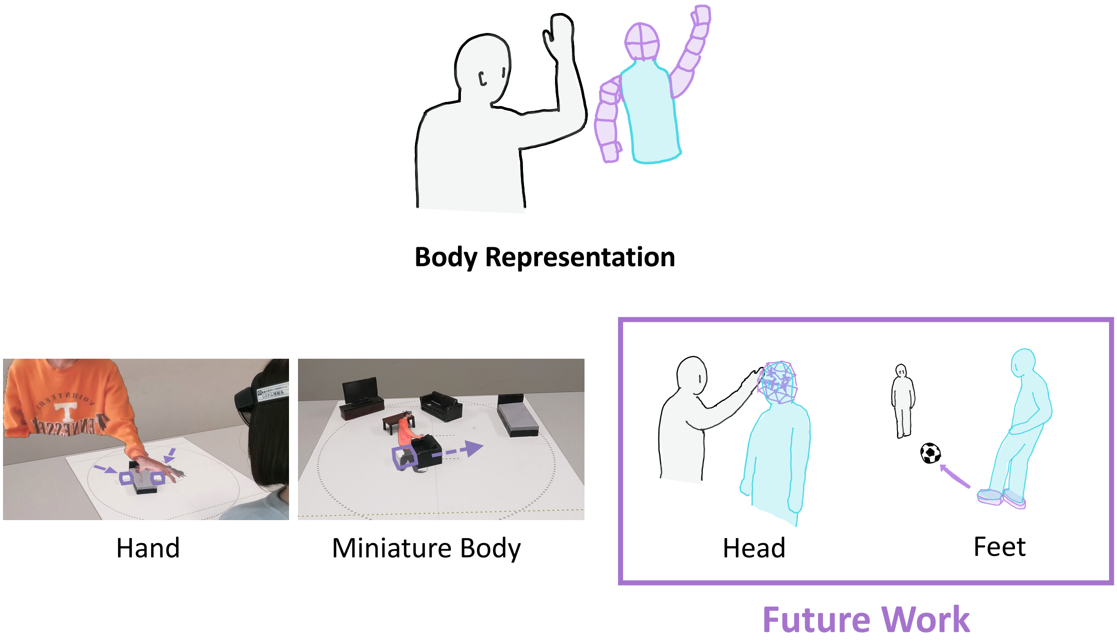

Figure 6.1: Future Work: Body Representation

6.1.3 Expanding Hand Representation

In HoloBots, the shape of the remote user's hands could only be represented in two dimensions. However, by using robots that move in 2.5 dimensions, as proposed in *ShapeBots* [SZK+19] and *HapticBots* [SOS+21], it becomes possible to represent shapes in 2.5 dimensions. This allows remote users to move more complexly shaped objects and local users to experience a more realistic sense of touch when they come into contact with the remote user's hands.

6.1.4 Expanding Miniature Body Representation

Similarly, the representation of miniature bodies can be expanded by using robots that move in 2.5 dimensions. By utilizing those robots, it's possible to adjust the height of the robots to match the size of the virtual miniature body, enabling interactions appropriate to that height. For example, this allows for appropriate haptic feedback when moving the avatar of the remote user. Additionally, by installing a camera on top of the robot and varying the camera's height, instructions can be given from different perspectives, depending on the height of the miniature body.

6.2 Object Manipulation

HoloBots enabled shared manipulation of Tangible UIs and object actuation in two dimensions. However, by employing other types of robots, actuation in 2.5 dimensions and even in three dimensions becomes possible, further expanding the scope of manipulation.

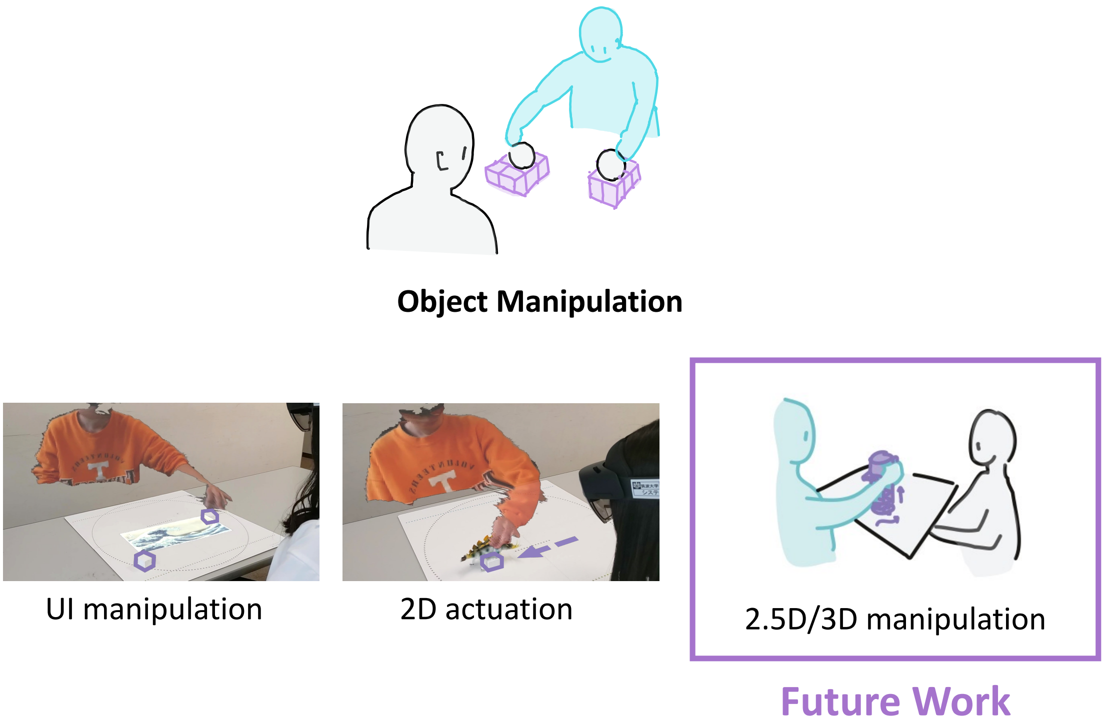

Figure 6.2: Future Work: Object Manipulation

6.2.1 2.5D and 3D Actuation

In HoloBots, it was possible to move objects by placing them on Toio robots. However, due to Toio's limitations, only movement on a two-dimensional plane was achievable. By integrating robots capable of 2.5-dimensional movement and drones capable of three-dimensional movements, a wider variety of interactions becomes possible. For example, combining with mobile robots capable of 2.5 dimensions movement can enable lifting objects. This can be used, for instance, in electronics work to lift and hold components for assembly or guidance. Additionally, using drones allows for moving and positioning objects in three dimensions. Attaching sticky notes to drones, for example, can facilitate brainstorming using three-dimensional space. In storytelling, three-dimensional movement can expand the range of expression.

6.2.2 Expanding 2D Actuation

The use of small Toio robots limited the movement of objects to those that are small and lightweight. However, by using large-size mobile robots like *Kachakka* [1] or cleaning robots, as seen in *RoomShift* [SHZ$^+$20], it becomes possible to move larger objects such as furniture and sports equipment like balls. This could enable collaborative interior arrangements and games that involve larger objects, like soccer. Additionally, as demonstrated in *HERMITS* [NLT$^+$20], using shells to attach multiple mobile robots together can amplify the moving power, further expanding the capabilities of moving larger objects.

6.2.3 Expanding UI Manipulation

In HoloBots, it was possible to perform tangible UI manipulations collaboratively using multiple small robots. This can be expanded by using mobile robots equipped with attachments, as was done in *HERMITS* [NLT$^+$20]. For example, by installing controllers such as joysticks, sliders, or knobs on top of the robots, more delicate and complex interactions can be facilitated. These enhancements could allow for a more nuanced control and a richer interaction experience in various applications.

[1] https://kachaka.life/

Chapter 7

Conclusion

In this thesis, I proposed the concept of telepresence using a collective of robots, which efficiently realizes diverse body representations and a variety of physical interactions using multiple robots. As the first step towards this realization, I developed the telepresence system HoloBots, utilizing mobile robots synchronized with the holographic avatar. With HoloBots, I demonstrated that the remote users can physically engage with local users and the local environment, enabling them to touch, grasp, manipulate, and interact with tangible objects as if they were co-located in the same space. I explored the design space of HoloBots, including interaction techniques, such as object actuation, virtual hand physicalization, miniature body interaction, shared tangible interfaces, embodied guidance, and haptic communication. I demonstrated various applications for HoloBots, such as physical storytelling, remote tangible gaming, and hands-on instruction. A user study with twelve participants revealed that HoloBots significantly enhances co-presence and shared experiences in mixed reality remote collaboration, proving its scalability, deployability, and generalizability for a wide range of remote tangible collaboration scenarios. As future work, I identified broader interactions that could be made possible by employing a collective of other types of robots.

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4. 石橋遼, 田之頭吾音, 井原圭一, 川口一画. AR 空間内における視線およびコントローラを用いたオブジェクト操作手法, 第 30 回インタラクティブシステムとソフトウェアに関するワークショップ（WISS 2022）論文集, 宮城, 2022 年 12 月.

Posters and Demos

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Appendix A

Social Presence Questionnaire

Social Presence

Reference:
Internal Consistency and Reliability of the Networked Minds Measure of Social Presence https://web-archive.southampton.ac.uk/cogprints.org/7026/1/Harms_04_reliability_validity_social_presence_(Biocca).pdf

* Indicates required question

1. Participant number (参加者番号) *

2. Condition (条件) *

   Mark only one oval.

   - C1: Both
   - C2: Avatar
   - C3: Toio

3. Application (アプリケーション) *

   Mark only one oval.

   - A1: TangibleUI
   - A2: Storytelling
   - A3: Interior design
   - A4: Notification

4. I noticed the remote user. (私は遠隔ユーザに気づいた) *

   Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

5. The remote user noticed me. (遠隔ユーザは私に気づいた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

6. The remote user's presence was obvious to me. (遠隔ユーザの存在が明らかだった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

7. My presence was obvious to the remote user. (私の存在は遠隔ユーザに明らかだった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

8. The remote user caught my attention. (遠隔ユーザは私の注意を引いた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

9. I caught the remote user's attention. (私は遠隔ユーザの注意を引いた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

10. I was easily distracted from the remote user when other things were going on. (他のことが起きているときに、私は遠隔ユーザから簡単に注意を逸らされた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

11. The remote user was easily distracted from me when other things were going on. (他のことが起きているときに、遠隔ユーザは私から簡単に注意を逸らされた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

12. I remained focused on the remote user throughout our interaction. (私は、対話の間、遠隔ユーザに集中し続けた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

13. The remote user remained focused on me throughout our interaction. (遠隔ユーザは、対話の間、私に集中し続けた) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

14. The remote user did not receive my full attention. (遠隔ユーザは、私の注意を十分に受けなかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

15. I did not receive the remote user's full attention. (私は、遠隔ユーザの注意を十分に受けなかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

無題のセクション

16. My thoughts were clear to the remote user. (私の考えは、遠隔ユーザにとって、明確であった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

17. The remote user's thoughts were clear to me. (遠隔ユーザの考えは、私にとって、明確であった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

18. It was easy to understand the remote user. (私は、遠隔ユーザのことを理解しやすかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

19. The remote user found it easy to understand me. (遠隔ユーザは、私のことを理解しやすかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

20. Understanding the remote user was difficult. (私は、遠隔ユーザのことを理解することが難しかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

21. The remote user had difficulty understanding me. (遠隔ユーザは、私のことを理解することが難しかった) *

Mark only one oval.

	1	2	3	4	5	6	7	
全く	◯	◯	◯	◯	◯	◯	◯	強く同意する

22. If you have any reasons for these responses, please state them.（これらの回答に対し、理由があれば、記述してください。）

Appendix B

System Usability Scale (SUS)

System Usability Scale (SUS)

Please rate the 10 indicators listed below on a 5-point scale from 1 (Strongly disagree) to 5 (Strongly agree).

(下記に書いた１０の指標について、１（まったくそう思わない）～５（非常にそう思う）の５段階評価を行ってもらいます)

* Indicates required question

1. Email *

2. Participant number (参加者番号) *

3. Condition (条件) *

Mark only one oval.

- C1: Both
- C2: Avatar
- C3: Toio

4. I think that I would like to use this system frequently (このシステムをしばしば使いたいと思う) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

5. I found the system unnecessarily complex（このシステムは不必要なほど複雑であると感じた) *

Mark only one oval.

	1	2	3	4	5
	◯	◯	◯	◯	◯

6. I thought the system was easy to use (このシステムは容易に使えると思った) *

Mark only one oval.

	1	2	3	4	5
	◯	◯	◯	◯	◯

7. I think that I would need the support of a technical person to be able to use this system (このシステムを使うのに技術専門家のサポートが必要とするかもしれない) *

Mark only one oval.

	1	2	3	4	5
	◯	◯	◯	◯	◯

8. I found the various functions in this system were well integrated (このシステムにあるさまざまな機能がよくまとまっていると感じた) *

Mark only one oval.

	1	2	3	4	5
	◯	◯	◯	◯	◯

9. I thought there was too much inconsistency in this system (このシステムでは、一貫性のないところが多くあったとおもった) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

10. I would imagine that most people would learn to use this system very quickly (たいていのユーザは、このシステムの仕様方法について、素早く学べるだろう) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

11. I found the system very cumbersome to use（このシステムはとても扱いにくいと思った) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

12. I felt very confident using the system (このシステムを使うのに自信があると感じた) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

13. I needed to learn a lot of things before I could get going with this system (このシステムを使い始める前に多くのことを学ぶ必要があった) *

Mark only one oval.

1	2	3	4	5
◯	◯	◯	◯	◯

Appendix C

NASA Taskload Index (NASA-TLX)

NASA-TLX

English: https://www.keithv.com/software/nasatlx/nasatlx.html
Japanese: https://www.keithv.com/software/nasatlx/nasatlx-ja.html

Please complete your answers on the above website and paste the results below.
(上記のサイトにて回答を行い、結果を以下に貼り付けてください)

Please paste all decimal points.
（小数点以下はすべて貼り付けてください）

* Indicates required question

1. Participant number (参加者番号) *

2. Condition (条件) *

Mark only one oval.

- C1: Both
- C2: Avatar
- C3: Toio

3. Mental Demand (知的・知覚的要求) *

4. Physical Demand (身体的要求) *

5. Temporal Demand (タイムプレッシャー) *

6. Performance (作業成績) *

7. Effort (努力) *

8. Frustration (フラストレーション) *

9. Overall (総合) *

10. What do you think is the reason for this result? (この結果の要因として何が考えられるか)