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Master's Thesis
Academic Year 2021

Virtually Augmented Multipresence Robots: Remote Play to Facilitate Ambient Co-presence

Keio University
Graduate School of Media Design

Ragnar Thomsen

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Ragnar Thomsen

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Abstract of Master's Thesis of Academic Year 2021

Virtually Augmented Multipresence Robots: Remote Play to Facilitate Ambient Co-presence

Category: Design

Summary

Loneliness is an increasing health concern in the developed countries, yet modern communication technologies such as SNS fail to address this issue. At the same time, telepresence robots are becoming ubiquitous in our everyday lives. While a promising technology, we identify several issues with current mobile robotic telepresence systems: they are generally designed for one to one communication only, the robots tend to have a limited set of affordances and the continuous transmission of audio and video raises privacy concerns. To address these issues, we propose a new type of robots: virtually augmented multipresence robots. Virtually augmented multipresence robots facilitate physical ambient co-presence between non-collocated users through remote play. We developed a proof of concept prototype based on Haru, a social robot currently being developed by Honda Research Institute Japan. The proof of concept prototype was evaluated in an AB test, and while our pilot study remained inconclusive, anecdotal evidence suggests that virtually augmented multipresence robots do have the potential to facilitate co-presence among non-collocated users. We propose to conduct a field trial with a larger sample size as a next step.

Keywords:

human-robot interaction, game design, co-presence, multipresence, mixed reality

Keio University Graduate School of Media Design

Ragnar Thomsen

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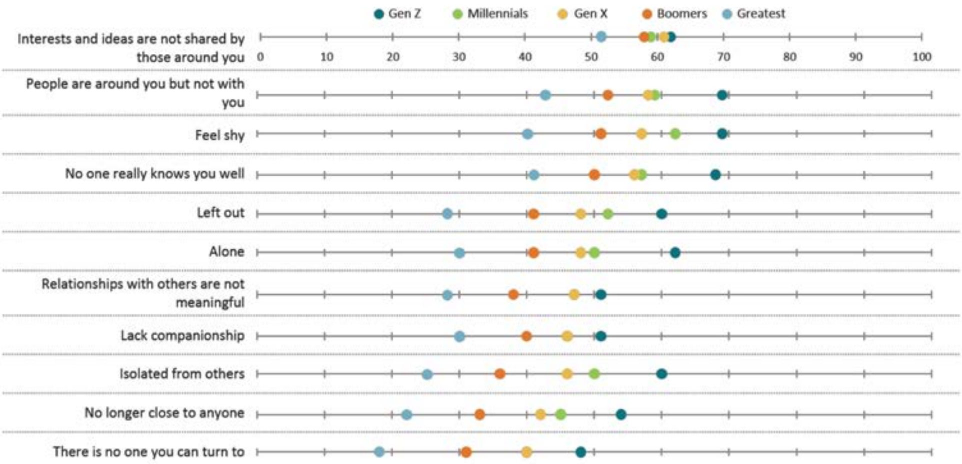
Chapter 1
Introduction

1.1. Loneliness, a Public Health Risk



(Source: Cigna U.S. Loneliness Report 2018 [1])

Figure 1.1 Loneliness in U.S. adults itemized by generation

Loneliness is a serious health issue, with some experts calling it a public health risk [2]. Loneliness has been linked to depression [3], and is adversely associated with physical and mental health [4].

Moreover, loneliness has been linked to increased mortality [5]. A 2013 article based on data from English households suggests that loneliness increases the risk of death for elderly people by more than 26 percent [6]. A more recent 2018 report by Cigna [1] that is based on data from over 20,000 US adults states that ”loneliness has the same impact on mortality as smoking 15 cigarettes a day, making it even more dangerous than obesity”.

But loneliness is not just an issue amongst the elderly. According to the same report, most Americans are lonely. And in fact, generation z and millennials are lonelier than the older generations (see Figure 1.1).

A 2020 report [7] suggests that "coronavirus loneliness" is 70 percent more common among millennials than baby boomers. The same report goes on to state that "one in three respondents in the U.S. is affected by coronavirus loneliness". It appears that loneliness has been rising due to the COVID-19 pandemic, and especially so among the younger generations. However, loneliness rates have been rising since before the COVID-19 pandemic. In a 2017 interview with the Washington Post [8], former U.S. surgeon general Vivek Murthy speaks of a "loneliness epidemic", warning that rates of loneliness are increasing. According to a 2006 study [9], there has been a significant increase of social isolates in the U.S. from 1985 to 2004 .

The issue of increasing rates of loneliness is not limited to the anglosphere. Also in Japan where social isolation sometimes leads to "kodokushi", it is becoming increasingly difficult for people to "establish and maintain close human connections" [10]. As of 2020, it is estimated that more than one million people in Japan are leading solitary lives as "hikikomori" [11]. Experts see people living in Japan across all ages at risk of becoming more isolated during the COVID-19 pandemic [12].

1.2. Social Networking Services

More than at any other point in human history before, today's telecommunication technologies make it easy and effortless for people to stay connected. Social networking services (SNS) allow us to connect to friends, acquaintances and strangers from any location in the world at any time. It is curious to see loneliness on the rise specifically in those countries where modern communication technologies such as SNS are the most accessible. It is even more curious then to see that loneliness is increasing at the highest rates among generation z and millennials - those generations where SNS literacy and its adoption rates are the highest.

While it is intuitive to believe that SNS usage might alleviate loneliness, studies prove the opposite. Indeed, frequent SNS exposure is commonly linked to increased levels of loneliness [13, 14] . However as of today, while experts agree that time spent on social media is correlated with self-reported loneliness, the exact reasons for this correlation remain unclear. One possible reason might be what is colloquially known as "FOMO": The "fear of missing out" on important life events of peers while simultaneously watching their lives unfold through their social media feeds as a passive spectator. Madianou [15] calls this "peripheral, yet intense awareness of others" ambient co-presence, arguing that this phenomenon has "powerful emotional consequences". According to her findings, these emotional consequences were negative for those people with weak relationships, but positive for people with strong relationships. Going on that people with strong relationships would associate ambient co-presence with "low-level emotional reassurance". A 2016 study [16] finds that image-based SNS platforms such as Instagram can ameliorate loneliness. These findings suggest that, despite being commonly associated with loneliness, SNS exposure does have the potential to positively influence people's well-being.

It is important to note that the majority of widely adopted SNS platforms such as Facebook, Messenger, Instagram, Line, Telegram or Whats App are all being operated by large companies with a business incentive. These platforms are primarily designed to be intricate retention and monetization machineries with the goal of being as profitable as possible. Ensuring the well-being of their users is not always in the best interest of these companies - especially when the users' unwell-being is profitable. Facebook for example, who owns 3 of the 6 SNS platforms listed above has been involved in several controversies surrounding their involvement in the currently still ongoing Myanmar genocide [17, 18]. Some claim that Facebook is profiting off of hate speech and hence not taking strong action against it [19].

1.3. The Future of Technology-Mediated Communication

1.3.1 Virtual Avatars

With our technologies ever evolving, so do the ways in which we communicate. We can see a noticeable trend towards avatar-based communication: As of 2017 [20], the social avatar application "Bitmoji" was the number one most downloaded mobile application in the U.S., U.K., France, Canada and Australia. Facebook is currently developing "Horizons" [21], a virtual reality avatar-based social network. As of today, an invite-only beta version of Horizons has been launched.

1.3.2 Physical Avatars

Not only virtual avatars are rising in popularity. When first released in 2015, Softbank's social robot "Pepper" was sold out within one minute [22]. Physical avatars in the form of robots are becoming more affordable and thus more widely adopted. A 2015 study finds that the physical presence of robots leads to them being perceived more positively than virtual agents [23]. This might be one of the reasons why telepresence robots are gradually becoming pervasive in our everyday lives. Today, telepresence robots are mostly being used in business, healthcare and educational institutions. However the market for telepresence robots is predicted to experience a strong growth over the next five years [24], so there is a chance that telepresence robots will eventually find their way into people's homes and be used for private communication, too.

1.3.3 Social Games

Designed to be gameplay experiences centered around social interaction, social games blur the line between video games and SNS. The aforementioned Facebook's "Horizons" is a highly gamified avatar-based SNS platform. The most successful online games today incorporate extensive social features. Last year, Epic games has launched a new "Party Royale" game mode [25] for their game Fortnite that is specifically intended to be used for organizing social gatherings. Roblox [26], an online game with a strong emphasis on social interactions has an average of 150 million monthly active users as of today. Tami Bhaumik [27], vice president of marketing and digital civility at Roblox, sees the future of social media in social online games.

1.4. Proposal

We believe that the future of technology-mediated communication is at the intersection of SNS, robots as embodied avatars and social games. We propose multipresence robots: virtually augmented social robots that act as mediators between two or more physical and/ or virtual spaces.

Multipresence robots combine a robot's advantage of physical presence [23] with the opportunities of image-based platforms [16] and the intentionality of play to facilitate a form of physical ambient co-presence [15] between non-collocated users.

1.5. Contributions

- A virtual twin can allow robots to be present in a virtual and physical space at the same time. We propose a design that facilitates physical co-presence by capitalizing on the ability of robots to be present at multiple locations at once.
- The physical presence of robots makes them uniquely suited to facilitate co-presence among non-collocated users. However, the affordances of robots are limited. We propose a method to enhance a robot's affordances through virtual augmentation.
- Online games already succeed at facilitating co-presence, but research on play with robots is scarce. Our research addresses this literature gap.

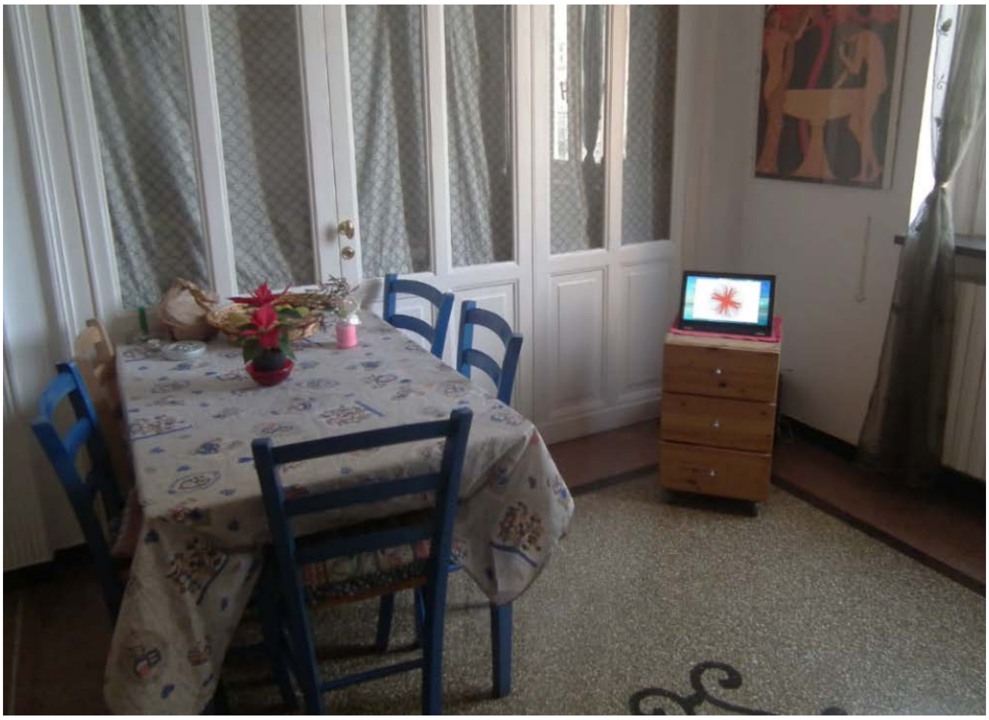
1.6. Thesis Structure

The thesis consists of six chapters. Chapter 1 introduces the problems that our research aims to address. Chapter 2 is a review of related works and literature in the fields of applied robotics, human-robot interaction, human-computer interaction, game design and the cognitive sciences. In Chapter 3, we discuss the design considerations and potential applications for multipresence robots. Chapter 4 describes the implementation of the multipresence robot concept at the example of social robot Haru, which is currently being developed by Honda Research Institute Japan. A study was conducted to evaluate a proof of concept prototype, which will be discussed in chapter 5. Chapter 6 concludes our research findings, highlighting opportunities for future research in this field.

Chapter 2
Literature Review

2.1. Ambient Co-Presence Technologies

2.1.1 Ambient Displays



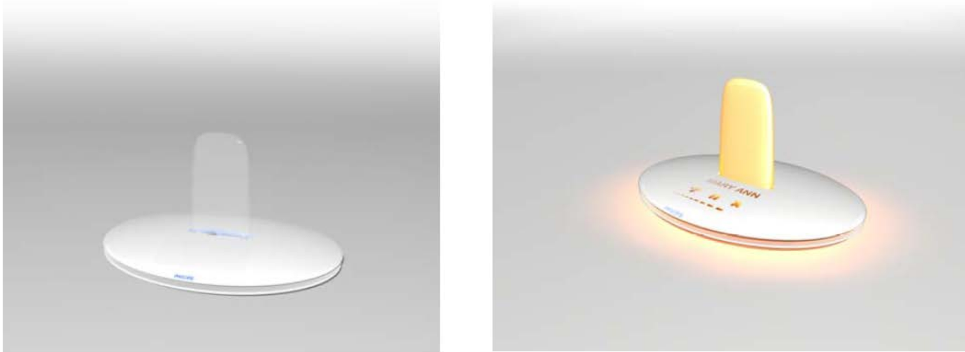
(Source: Promoting Social Connectedness through Human Activity-Based Ambient Displays [28])

Figure 2.1 Human activity-based ambient displays

Davis et al. [28] introduce a bidirectional ambient display platform to enhance social connectedness. The ambient displays (see Figure 2.1) were designed to be used among elderly people and their caregivers. Both the caregivers and the elderly would carry a smartphone with them throughout their daily lives, which would be mounted to their waist; using the smartphones' embedded gyroscope and accelerometer sensors, the wearers' physiological data would be recorded through what Davis et al. describe as a "human activity recognition" system. The physiological data is then streamed to the ambient displays, where it is being classified and displayed in real time as visual shapes. Based on a field trial (N=12) Davis et al. conclude that using this technology increases the participants closeness for both the elderly and caregivers. While the sample size of this field trial is low, it correlates with the findings of Pittman et al. [16] who argue that image based SNS exposure is adversely associated with loneliness and has a positive impact on emotional well being. According to their qualitative analysis, "monitoring" and "surveillance" were recurring topics during the field trial. Indeed, real-time streaming of physiological data offers opportunities for surveillance. According to Madianou [15], this might have a positive emotional influence on the co-presence experience of pairs with a high interpersonal closeness, while this kind of technology could have negative effects on the emotional experience of pairs with lower interpersonal closeness.

2.1.2 Ambient Telephony

Arguing that telephonic communication in the household is providing little experience of co-presence, Emparanza et al. [29] suggest the use of an ambient telephony system. The system would consist of several microphones and loudspeakers that are distributed around the house, changing the sound according to a person's current location. Based on an exploratory study, they conclude that this system resulted in higher levels of social presence compared to using a cordless phone. Based on their findings from the exploratory study, an improved prototype was developed (see Figure 2.2). This prototype would mediate the conversation by producing different shapes of light during a call. According to a second study, the improved prototype was received more favorably than the previous iteration. However, they then go on to identify a dilemma: While rich visual feedback was thought to be beneficial for mediating intimacy and immediacy, it is challenging to render this type of visual feedback in a light-based ambient display.



(Source: Ambient telephony: Designing a communication system for enhancing social presence in home mediated communication [29])

Figure 2.2 Ambient telephony prototype

2.1.3 Play and Ambient Co-Presence

The concept of ambience is commonly associated with aural experiences. The sounds and noises surrounding us create an ambience for us to experience. This notion is reflected in the music genre of "ambient music", which is concerned with creating a particular ambience, an atmosphere rather than what we typically associate with music. In "Mobile games and ambient play", Hjorth and Richardson [30, p. 105] argue that ambience is not only an aural experience. In the context of mobile games, they describe ambience as a culmination of "a game's texture, affect and the embodied modality of the player". If we understand mobile gaming as "ambient play", we can understand game play as something that "takes place both in and out of games". This let's us examine how mobile games negotiate intimacy and a sense of place between players and game worlds, but also between players and other players. As such, ambient play "re-contextualizes gameplay as part of our broader embodied experience of being-in-the-world" [30, p. 105].

Pokemon Go

In "Haptic ambience: Ambient play, the haptic effect and co-presence in Pokemon GO", Apperley et al. [31] discuss how the multi-modal affordances of Pokemon Go

[1] contribute to facilitating a sense of co-presence among players. They argue that, in utilizing social media features along with the smartphone's camera, Pokemon GO allows players to "experience the feeling and touch [...] through affective resonance". Players are interacting within a "matrix of embodied experiences" that extends the play experience through touch, gesture and spatial practice. In "A Sense of Belonging: Pokemon GO and Social Connectedness", Vella et al. [32] examine Pokemon Go as a social ambience experience and conclude that it "produced a sense of belonging, linked to a sense of place, as well as facilitating conversations with strangers and strengthening social ties", thus facilitating social connectedness between players.

World of Warcraft

It seems that online games such as Massive Multiplayer Online Role Playing Games (MMORPGs) succeed at facilitating co-presence among players. The 2006 study "“Alone Together?” Exploring the Social Dynamics of Massively Multiplayer Online Games" [33] examines the MMORPG "World of Warcraft" [2] with interesting results: Despite social features existing, joint activities in World of Warcraft are "not very prevalent". However, a 2016 study [34] finds that World of Warcraft players experience less loneliness in the game than in the real world. While the game has changed considerably over the course of 10 years, the core gameplay experience is still the same. Hence, the results are comparable. If joint activities are not very common among players, then why do they not feel lonely? While this needs to be further investigated, a possible answer is that MMORPGs like World of Warcraft establish a strong sense of ambient co-presence among players: Players might experience companionship and social connectedness without having to actively engage in activities with each other.

1 Niantic, Pokemon GO, (2016)

2 Blizzard Entertainment, World of Warcraft, 2004

2.2. Telepresence

2.2.1 Origin

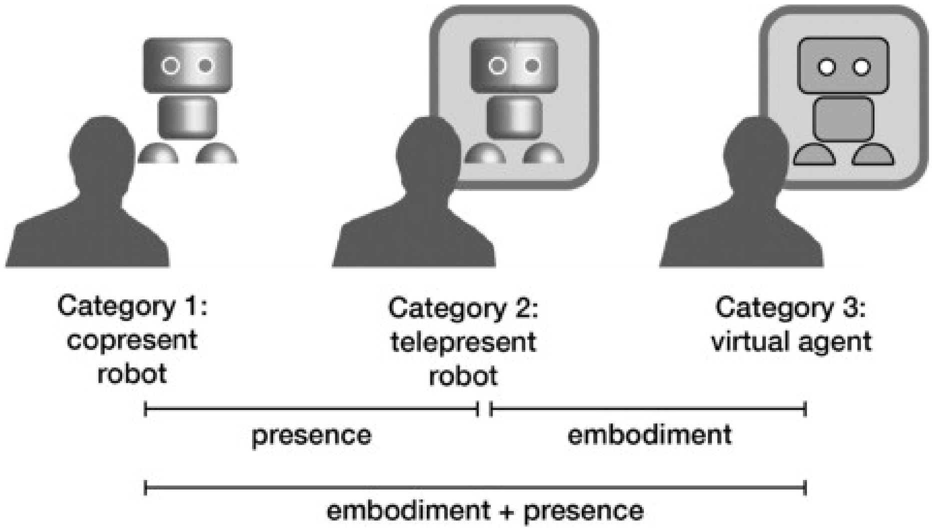
In a 1980 article, Minksy [35] outlines what they describe as a "telepresence system", thereby coining the term "telepresence". Telepresence describes the feeling of being present in a location other than one's own. Following its inception, the term has been widely used in the field of HCI literature to describe systems that allow users to extend their presence into remote locations.

2.2.2 Challenges

"Social connectedness", "closeness", "presence" - we have an intuitive understanding of what these words mean. Yet, it is difficult to clearly define these nuanced phenomena in the context of technology-mediated communication [36]. Still, Bel et al. [37] argue that "social connectedness" is considered "one of the major outcomes of successful (mediated) social interaction" in the field of Human-Computer Interaction. With the behavioral sciences offering quantitative methodologies that allow us to evaluate phenomena such as social connectedness [38] and co-presence [39, 40], a question arises: What factors then contribute to the success of technologies that mediate social connectedness or co-presence in the context of human-robot interaction?

Physical Presence

The previously mentioned 2015 study by Jamy [23] surveyed a total of 64 previous studies comparing the effects of phyiscal collocated robots, telepresent robots and virtual agents. Their findings suggest that there is no difference in the interactive experience of participants with virtual agents compared to telepresent robots (i.e. robots that are non-collocated and visible through a screen, see figure 2.3). However when compared to virtual agents and telepresent robots, the physical presence of collocated robots consistently leads to more favorable psychological responses from participants. Hereby, the shape of the physical embodiement is not a deciding factor. Among humanoid morphologies, zoomorphic and caricaturesque embodiements were also evaluated as part of the surveyed studies. These



(Source: The benefit of being physically present: A survey of experimental works comparing copresent robots, telepresent robots and virtual agents [23])

Figure 2.3 The three categories of presence

findings suggest that the shape of the robot does not matter as much as its physical presence - caricaturesque robots with a physical presence might be perceived more positively than photorealistic virtual agents. A 2021 study [41] supports this argument, stating that interacting with more than one robot can have the "potential to impact psychological needs, even when the robots have no humanoid features".

Visual feedback

While physical presence is a strong factor, Pousman et al. [42] argue that for mediating social presence between users, the greatest difference lies in visual versus non-visual feedback. This coincides with the findings of Emperanza et al. [29]: visual feedback seemed to be more effective at mediating intimacy and immediacy in ambient telephony systems.

Interpersonal Closeness

A 2020 study [43] examines the effects of interpersonal closeness between participants communicating through a telepresence robot: Their findings suggest that the interpersonal closeness of the participants influenced the interaction experience more than any other variable. In the experiment, robot operators in pairs with higher interpersonal closeness felt more present than in pairs with lower interpersonal closeness. However, the interlocutors [3] perceived the remote robot-operator's presence similarly regardless of interpersonal closeness. In conclusion, while interpersonal closeness seems to be an important factor for the presence experience of robot operators, it might not be a contributing factor for the presence experience of the interlocutors.

Personalization

(Source: You're Wigging Me Out! Is Personalization of Telepresence Robots Strictly Positive? [44])

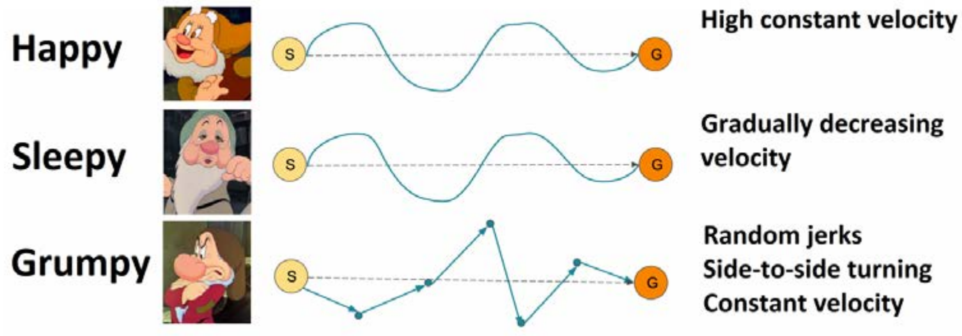
Figure 2.4 Robots with wigs

When communicating through a telepresence robot, it is intuitive to believe that robot personalization might increase the feeling of presence between robot operator and interlocutor. The aforementioned study [43] on interpersonal closeness in telepresence robot interaction however finds that there is no association

3 The conversation partner of the tele-operated robot.

between robot customization and perceived co-presence. Indeed, a 2021 study by Fitter et al. [44] finds that customized robots can be perceived as less approachable and more unpleasant, specifically telepresence robots outfitted with wigs (see Figure 2.4).

Emotional Cues



(Source: Distinguishing Robot Personality from Motion [45])

Figure 2.5 Robot motion personalities

In a 2020 study, Daly et. al [46] argue that robots which exhibit emotional behaviors are more likely to be assisted by people than robots that do not exhibit emotional behaviors. Another 2020 study [45] suggests that users are able to distinguish robot personalities based on robot motion alone. Robots would move in different trajectories, depicting "Happy", "Sleepy" and "Sad" behavior" (see Figure 2.5). Empathy or social closeness with robots is a field of study that warrants further research [47], however based on Daly et al.'s [46] findings, we can assume that a robot capable of expressing emotional behaviors might also be more capable to facilitate a sense of connectedness.

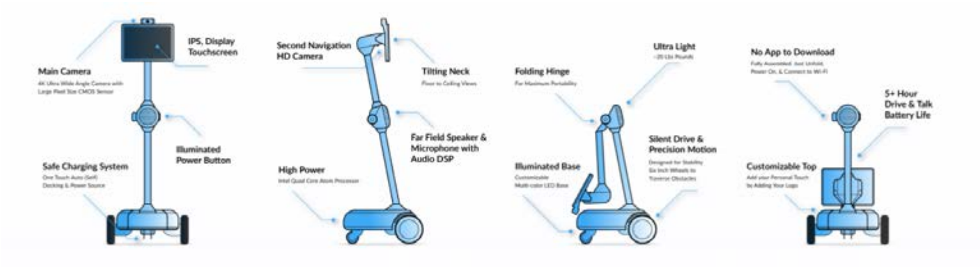
2.2.3 Telepresence Robots

The most common telepresence systems today are mobile robotic telepresence (MRP) systems. Kristoffersson et al. [48] describe MRP systems as follows:

"Mobile robotic telepresence (MRP) systems are characterized by a video conferencing system mounted on a mobile robotic base. The system allows a pilot user to move around in the robot's environment. The primary aim of MRP systems is to provide social interaction between humans. The system consists of both the physical robot (sensors and actuators) and the interface used to pilot the robot."

More commonly referred to as "telepresence robots", a 2017 study [49] indicates that mobile robotic telepresence systems have the potential to improve social connectedness in people with dementia and their carers. While consumer products are available, currently commercially available telepresence robots are still lacking in aspects such as maneuverability, controllability and autonomy [50].

Ohmni Telepresence Robot



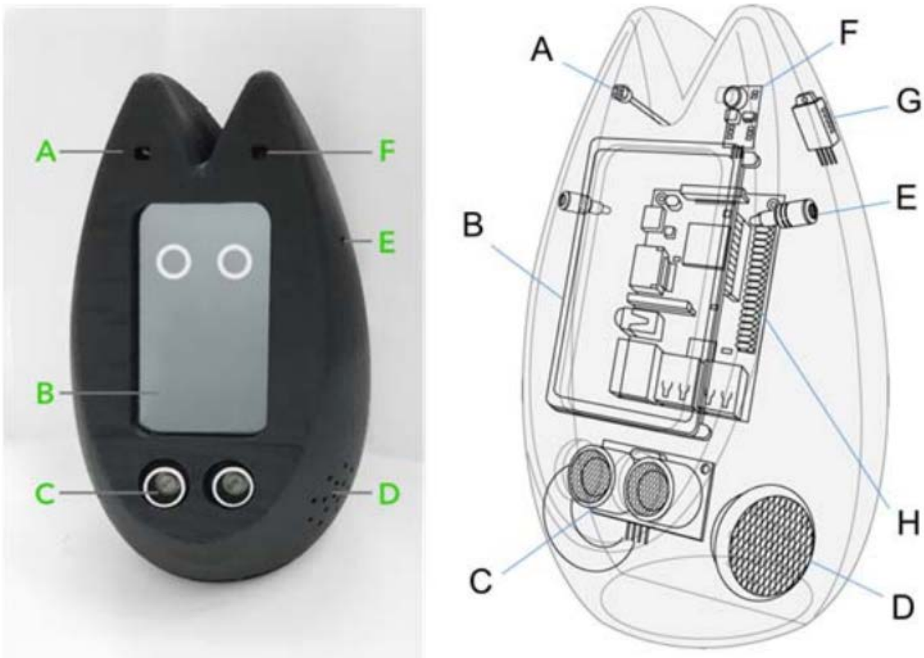
(Source: Ohmni Telepresence Robot [51])

Figure 2.6 Ohmni telepresence robot

The Ohmni Telepresence Robot (see Figure 2.6), manufactured by Ohmni Labs [51], serves as an example for a commercially available and widely used telepresence robot that fits the definition of Kristoffersson et al. [48]. For example, it is used in the aforementioned study by Fitter et al. [44]. The robot is characterized by a tablet-sized IPS panel that is mounted onto a movable base. The robot can rotate at six degrees of freedom and is remotely controlled by the robot operator.

Fribo

Addressing the issue that current telepresence robots are designed only for one to one communication, Jeong et al. propose "Fribo" [52]. Fribo (see Figure 2.7) is a



(Source: Fribo: A Social Networking Robot for Increasing Social Connectedness through Sharing Daily Home Activities from Living Noise Data [52])

Figure 2.7 Fribo

telepresence robot that mediates sound between users by analyzing the occupants' living noise data and sharing it to close friends. Hereby, the robot acts as a sound-mediator that filters unwanted noise and only shares living noise that is desired by its users. Jeong et al.'s field study suggests that Fribo successfully facilitates a sense of "virtual co-residence" between users. While successful as a pilot study, the authors note that sharing more information beyond living noise data would prove beneficial to forming a "virtual living space". However, while sharing more information might improve the sense of realism, it would be "important to find an optimum point where privacy infringement is minimized while maximizing the active connection between users".

2.3. Play With Robots

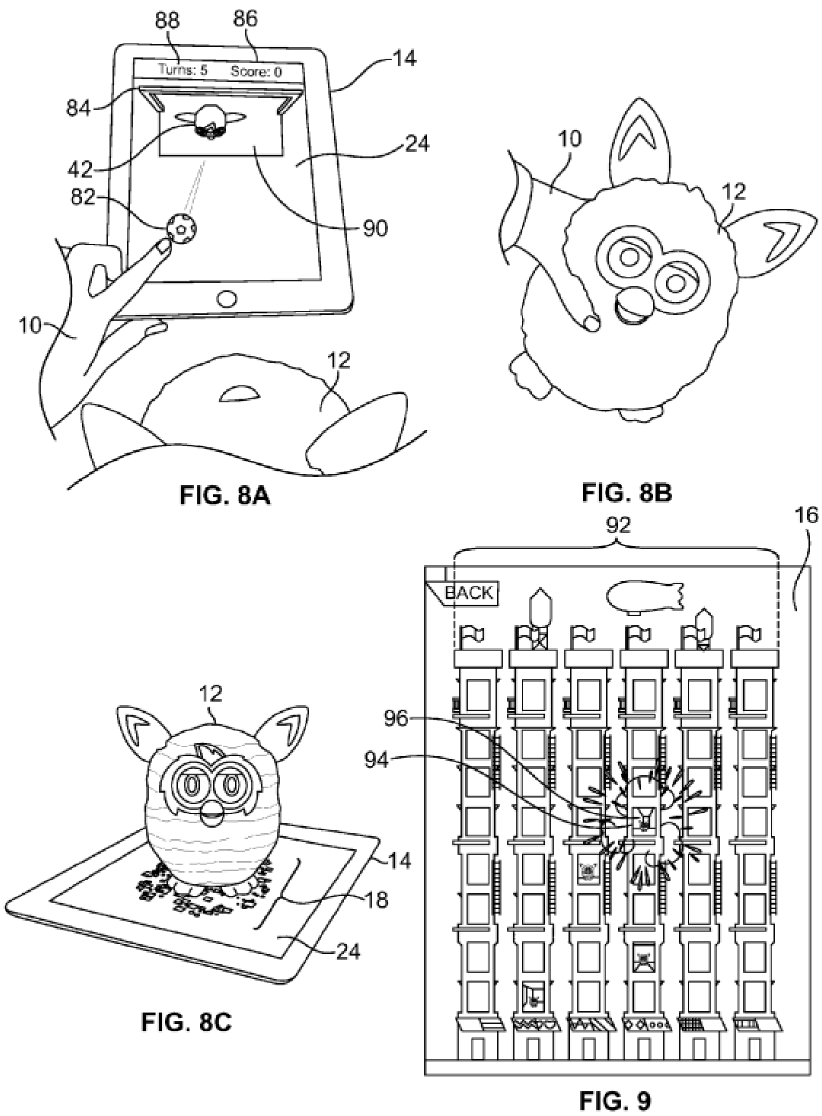
2.3.1 History

Robot toys have been popular among children since the last century: In 1998 and 1999, "Furby" was so popular that it prompted the Canadian health ministry to conduct a study [53] on whether the electronics inside it would interfere with medical equipment. Robot toys such as Furby are still popular today. But despite robot play being an inherent part of our culture, research on this subject matter is scarce.

2.3.2 Furby

Manufactured by Hasbro, the robot toy Furby is still in production today. Since its inception in 1998, Furby's design has been reiterated multiple times. In a 2017 patent [54] for a "Three Way Multidirectional Interactive Toy" (see figure 2.8), Judkins et al. describe Furby's most recent design as follows:

"Systems and methods for interaction between a user and a plurality of toys is disclosed where an interactive physical toy character senses inputs from a player and from a virtual toy character in a virtual environment. The virtual toy character likewise senses inputs from a player and a physical toy character so that bidirectional, multi-way gameplay involving a player, a physical toy and a virtual toy in a virtual environment is achieved."



(Source: U.S. Patent 9,675,895 B2 [54]

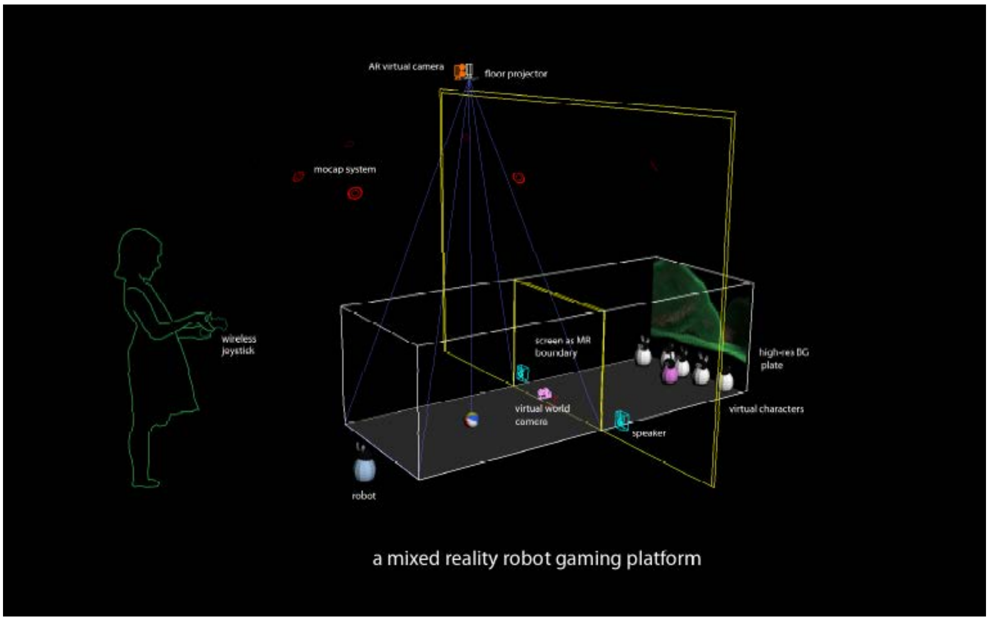
Figure 2.8 "Three Way Multidirectional Interactive Toy", Furby

The modern Furby can be connected to a tablet that extends its material presence into a virtual play space. By design, a large part of the play experience with Furby is centered around nurturance: As an example, users can feed Furby from a selection of virtual foods displayed on the tablet. Based on the food choice, the physical Furby will then react in response to it. As depicted in Figure 2.8, the user can play various mini games with Furby through the tablet. Depending on the game, the physical Furby will react in response to what's happening inside the tablet.

Describing toy robots as "harbingers of autonomous technologies that have social agency", Chesher [55] argues that Furbys are increasingly prominent in the popular imagination today. In a 2018 article, Marsh [56] suggests that Furby's autonomy gives it the ability to influence how children engage with it. This is a shift from non-digitally augmented toys that have no inherent agency in the play experience of children.

2.3.3 Mixed Reality Play

In "Exploring Mixed Reality Robot Gaming", Robert et al. [57] expand on the concept of extending a play space from the material world into the virtual world. "Miso" is a tele-operated robot that is linked to a projected virtual environment (see Figure 2.9). Controlled with a virtual joystick, Miso can interact with a virtual ball that is projected onto the floor. The ball can be bounced between the physical robot Miso and several autonomous virtual characters that are projected onto a wall in front of Miso and the player. Miso's position in the physical world is mapped to a position in the virtual world, thus creating what the authors call a "hybrid space" - a fantasy world that is connected to the material world through a tangible interface. This exploratory study was not formally evaluated, but the authors conclude that mixed reality gaming holds "a tremendous amount of potential for new ways to entertain, learn and communciate".



(Source: Exploring mixed reality robot gaming [57])

Figure 2.9 Mixed reality gaming

2.4. Virtually Augmented Robots

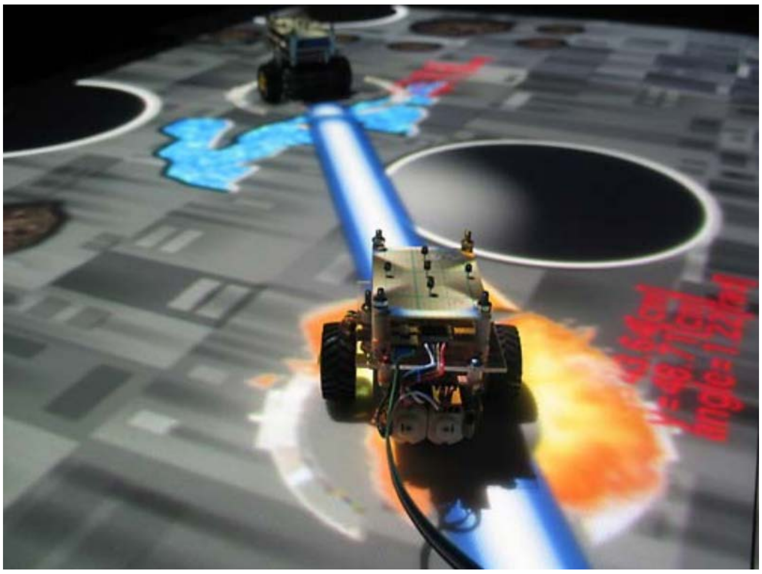
2.4.1 Robots and Virtual Worlds

In "Studying Virtual Worlds as Medium for Telepresence Robots", Juarez et al. [58] compare human-robot interactions in a physical space with human-robot interactions in a virtual recreation of the same physical space. They conclude that virtual worlds are not yet good enough to produce better results than direct human-robot interaction. This supports the argument of Jamy [23] that physical presence is an important factor for successful human-robot interaction. However, we argue that Juarez et al.'s [58] conclusion is premature and cannot be generalized, as only one specific virtual world has been evaluated as part of their study. In addition their virtual prototype was created in "Second Life" [4] , which does not offer the same graphical fidelity that modern professional game development

4 Linden Lab, Second Life (2003)

frameworks can provide. We argue that well crafted virtual worlds can have a positive influence on human-robot interaction, as previously suggested by Robert et al. [57].

2.4.2 Augmented Coliseum

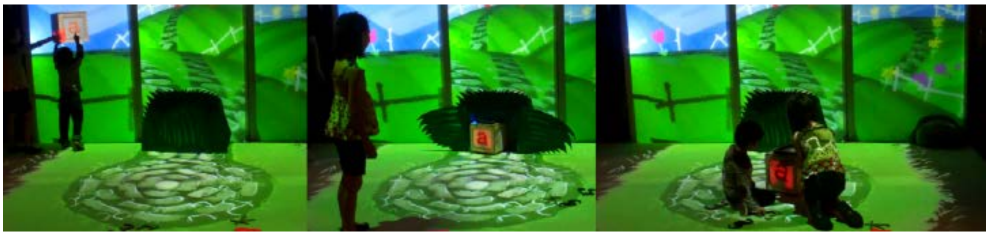


(Source: Augmented coliseum: display-based computing for augmented reality inspiration computing robot [59])

Figure 2.10 Augmented coliseum

In "Augmented coliseum: display-based computing for augmented reality inspiration computing robot", Sugimoto et al. [59] propose a system for augmenting a virtual environment with tangible interfaces. Small robots are synchronized with a virtual overlay in real time (see Figure 2.10) to enhance the affordances of the projected world. We argue that the small scale of the robots makes this experience phenomenologically different from the previously discussed "Exploring Mixed Reality Robot Gaming" [57]. While Robert et al. describe a system to virtually extend a tangible object (tele-operated robot), Sugimoto et al. propose a technology to enhance a virtual environment through tangible interfaces. Hence, the relationship of the virtual and the material are of a different quality.

2.4.3 Blended Reality Characters



(Source: Blended reality characters [60])

Figure 2.11 Blended reality characters

In their 2012 study, Robert et al. [60] propose a design concept for "Blended Reality Characters". Blended reality characters are able to maintain "visual and kinetic continuity between the fully physical and fully virtual". Their proposed character can freely move between the material world and a virtual world through a hutch (see Figure 2.11). Based on the results of a field study, the authors claim that this fluidity between the real and the virtual is intuitively accepted by the participants.

2.4.4 Virtual Twin

(Source: The virtual twin: controlling smart factories using a spatially-correct augmented reality representation [61])

Figure 2.12 Virtual twin

In industry settings, a digital representation of machine data is considered a digital twin. Typically, the machine data is represented in the form of 2D graphical user interfaces. Kritzler et al. [61] propose the concept of a virtual twin, which is an accurate virtual representation of machine data (see Figure 2.12). The virtual twin is a spatially correct arrangement of machinery at an industry site and can be accessed through a head mounted display, in the case of Kritzler et al., a Microsoft HoloLens. The virtual machinery is connected to their respective material counterparts, which allows users to interact with the virtual machinery to change the state of the on-site machinery (e.g. pressing on/ off buttons). Kritzler et al. claim that a virtual twin can "help factory managers, supervisors and service technicians to require less time on site". Referred to as Industry 4.0, virtual twins are slowly being adopted in industry settings. This demonstrates that it is technologically feasible for robotic interfaces to be connected to a virtual simulation, even at a large scale.

2.5. Summary

Based on our literature review, we summarize that the following factors as being beneficial to mediating presence:

- Physical presence [23]
- Visual Feedback [16, 29, 42]
- Ambience and Play [15, 30, 32]
- Privacy (i.e. control over shared information) [15, 28, 52]

We identify the following issues in current telepresence technologies:

- They are typically designed only for one to one communication
- They have limited affordances
- They do not offer rich visual feedback
- The continuous sharing of audiovisual information raises privacy concerns

Chapter 3
Design

3.1. From Telexistence to Multipresence

Around the same time as Minsky introduced the term "telepresence" [35], Susumu Tachi [62] coined the term "telexistence" to describe the feeling of "existing" at a physical location other than one's own . In the literature today, the term "telepresence" is more commonly used than "telexistence". One might argue that these terms are interchangeable, however we argue that they indeed describe different phenomena. The experience of being present at a location is phenomenologically different from the experience of existing at a location. For example: If I were to make a phone call, my voice would be present at the other end of the line. Yet, I am aware of the fact that my voice still also exists in my actual physical location. This could be considered a form of telepresence. However while the notion of telepresence is that one extends their presence into a different location, the notion of telexistence is that one's (entire) existence is moved into a different location. A person experiencing telexistence in this sense would cease to exist in their current physical location. Their entire existence would be shifted towards the other location. In a state of telexistence, we only exist at the tele-location.

Whether or not a person could ever truly experience a state of telexistence in this sense is open for debate. But while this state of telexistence may not be applicable to humans, it is indeed applicable to robots. A robot's body exists in the physical space. But a robot's mind - the software controlling the robot - is not bound to a robot's physical body. It could exist on a networked computer. Or in the cloud. It could even be decentralized and exist on multiple platforms simultaneously. When we think of robots, we tend to imagine them as physical bodies. This way of thinking might be useful when our goal is to create human-like robots. But robots don't have to exist in the same way that humans do. The notion of robots existing in a decentralized manner let's us approach human-robot interaction from a new perspective. We propose a new type of robots - robots that don't exist in one place, but in multiple places at once: virtually augmented multipresence robots.

3.2. Virtually Augmented Multipresence Robots

3.2.1 Concept

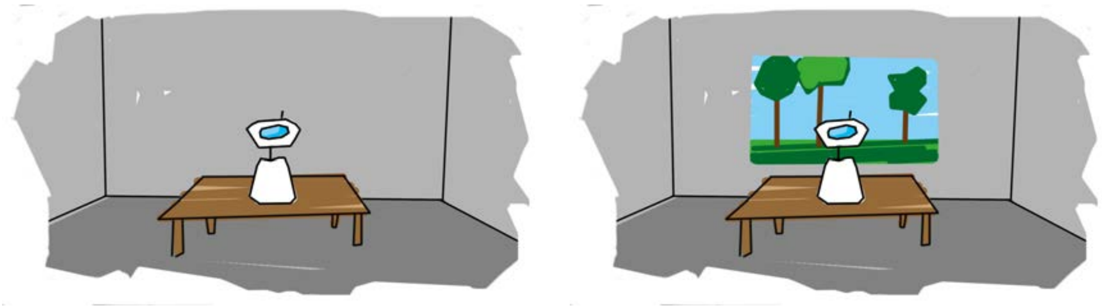
Virtually augmented multipresence robots are robots that exist in multiple locations at the same time. This allows them to act as mediators between remote locations. Through a form of remote play, virtually augmented multipresence robots thus establish a form of physical ambient co-presence between non-collocated users.

The virtually augmented multipresence robot concept consists of two components: a new method to virtually augment a robot's affordances and the concept of what we describe as a multipresence robot system.

3.2.2 Virtual Augmentation

As outlined in our literature review, current generation robots - and specifically stationary robots - tend to have limited affordances. Stationary robots typically don't have limbs, making them immobile (compare Figure 3.1a). However, some parts such as the head might be move-able. In addition to having some move-able parts, this type of robot typically features speech and/ or gesture recognition and comes with an embedded speech module. Stationary robots like this are becoming increasingly popular as toys and for home entertainment purposes.

Due to their immobility, stationary robots have limited affordances. Therefore, we propose a method to virtually augment a stationary robot's affordances by attaching a screen to the back of the robot (see Figure 3.1b). In the screen, we display a virtual environment. By synchronizing the robot with the virtual simulation, we can extend the robot's presence from the physical space into the virtual environment. If the robot turns its head, the camera rotation in the



(a) Conventional stationary robot (b) Virtual augmentation

Figure 3.1 Virtually augmented stationary robot

virtual space will move accordingly. By animating the robot's head movements and moving the virtual environment in the background, we can create the illusion of the robot walking through the virtual space. Depending on the model and particular features of the stationary robot that our concept is applied to, various results can be achieved.

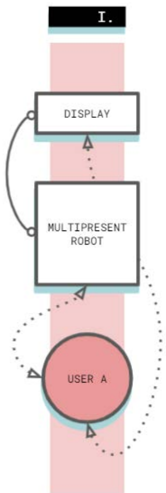


Figure 3.2 Virtual augmentation setup

As depicted in Figure 3.2, the robot is attached to a display that extends the robot's presence into a virtual environment. This is achieved through a virtual twin [61]. The robot's virtually augmented affordances allow it to communicate more effectively than without the virtual augmentation.

3.2.3 Multipresence Robot System

Multipresence robots are designed to facilitate co-presence between non-collocated users. Depicted in Figure 3.3a there are two remote locations 1 and 2. In each location, there is an instance of the multipresence robot. Both instances of the multipresence robot share the same location in the virtual environment. Therefore when looking at the robot, Person A1 and Person A2 will see the same image on the screen to the back of the robot. In addition, the robot's state in both locations is also identical at all times.

If Person A1 in Location 1 interacts with the robot (see Figure 3.3b), the robot will react to it leveraging on its virtually augmented affordances. As can be seen in Figure 3.3c, the robot in Location 2 will react to Person A1's behavior in the same manner as the robot in Location 1. For example, if Person A1 instructs the robot to walk into a certain direction, Person A2 will be able to observe the robot walking into that direction. Through this, the multipresence robot system creates a sense of co-presence between the remote users A1 and A2.

The multipresence robot system can not only facilitate co-presence among two non-collocated users, but also between groups of non-collocated users (compare Figure 3.3d). Persons A2, B2 and C2 can observe how the robot reacts to Person A1, B1 and C1's instructions and vice versa.

Creating a Blended Virtual Space

By creating a blended virtual space between remote locations, virtually augmented multipresence robots can not only connect two remote locations, but any number of remote locations. As depicted in Figure 3.4a, five instances of the multipresence robot exist in locations I to V. For each location I to V, there is a user A to E. At any of the locations and at any time, a user can interact with their respective instance of the multipresence robot. As expected, the multipresence robot system will respond to the user interacting with it. This means that, the robot instance in the user's location will react to the user's input. At the same time, the instance's

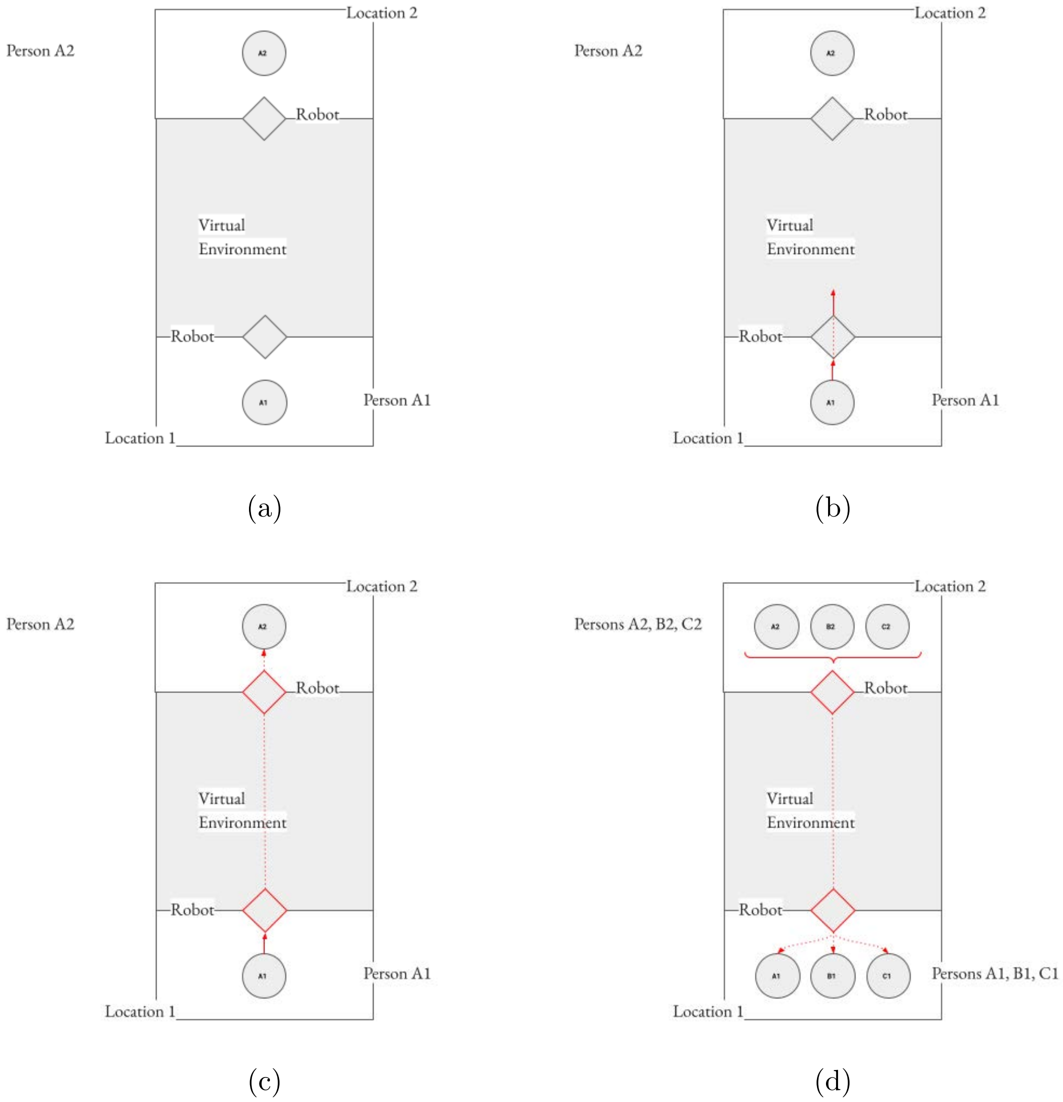
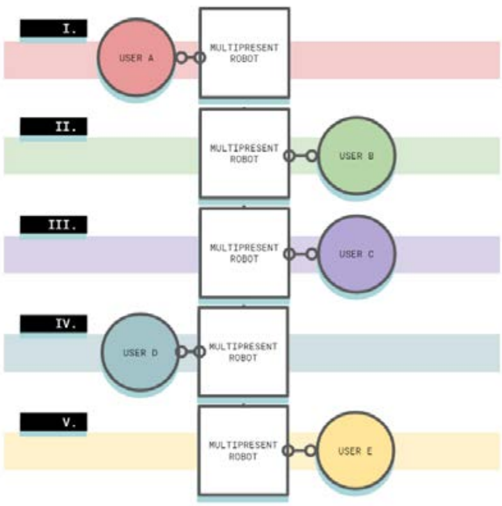
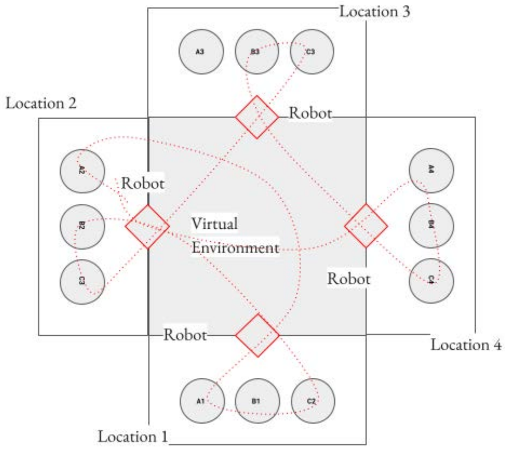


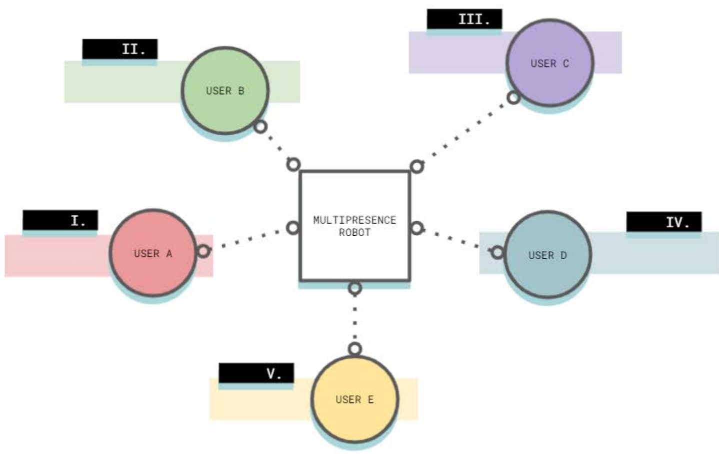
Figure 3.3 Multipresence Concept



(a) Mediation between spaces



(b) User relations



(c) Blended virtual space

Figure 3.4 Mediating between multiple spaces reaction will also be replicated to all other instances of the multipresence robot system. As a result, all other users will be able to observe the robot's response in their respective location. Thus, the instances blend the remote locations together into one virtual space (see Figure 3.4c): By blending the remote locations into a virtual space, the multipresence robot system acts as a mediator between any number of non-collocated users.

However as can be seen in Figure 3.4b, the relations between users will become more convoluted the more actors and remote locations are added to the virtually augmented multipresence robot setup.

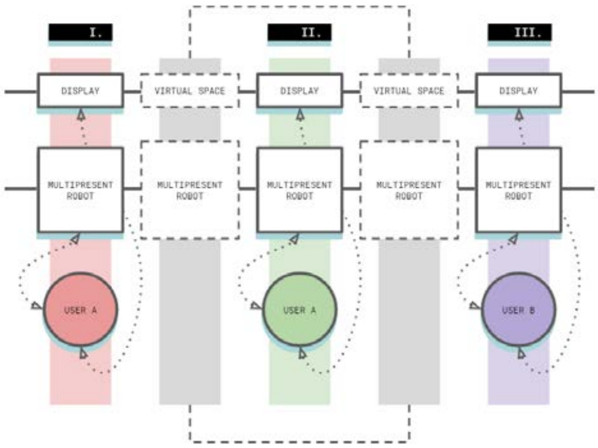


Figure 3.5 Schematic of a virtual ambient multipresence network

While in theory, non-virtually augmented robots can be utilized for a multipresence robot network, the attached displays allow the multipresence robot system's instances to blend the remote locations more effectively. As depicted in Figure 3.5, users A, B and C are situated in separate locations. Each location I to III is inhibited by an instance of the multipresence robot system. Each instance of the system is equipped with a display that extends the robot instance's presence into a virtual environment. Because all instances of the system are identical, the virtual simulation that is rendered in the display is the same for each location. Beyond augmenting each robot's affordances, the virtual environment itself is a space for interactive opportunities. Users can feel each other's shared relationship with the multipresence robot system not only through the robot instances, but also through the virtual simulation. The multipresence robot system exists in the virtual space just as much as it exists in the physical space.

Distinction from Previous Methods

While leveraging on similar technology to virtual twins [61], the here discussed virtual augmentation is functionally different from the virtual augmentation of a virtual twin. For a virtual twin, the virtual copy exists separated from the physical machinery. In our case, a virtual environment is layered on top of the physical robot. While our approach has similarities with Robert et al.'s [60] blended reality characters, there is an important difference: while blended reality characters shift between the physical and the virtual world, virtually augmented multipresence robots exist in both physical and virtual locations at the same time. As such, there are similarities with robot toys such as Furby [54]. However, while Furby and its simulation exist at the same time, they are only loosely interconnected across the spatial dimension, i.e. Furby's location in the material world is usually not synchronized with its virtual world. The state of virtually augmented multipresence robots is replicated to the virtual location in the same way as it is replicated to other remote physical locations. We believe that our virtual augmentation approach brings many advantages and opportunities for novel interactions.

3.3. Interaction Design

3.3.1 Multipresent Co-Inhabiters as Pets

While instances of a multipresence robot system respond to user's inputs, they also need to exhibit a certain degree of autonomy. Autonomous behaviors should incentivize users to interact with the instances in order to facilitate a sense of social presence. In a way, a multipresence robot system could be thought of as a multipresent pet - a tamagotchi [1] - that needs to be taken care of by multiple users in remote locations at the same time.

1 Bandai, Tamagotchi, 1996-present

Nurturance

In a 2021 study, Kamino et al. [63] find that sharing the experience of enjoying food can be beneficial for human-robot interactions and improve our relationship with robots. We therefore propose the design of an interaction model for a multipresence robot system to be centered around the concept of nurturance. This seems intuitive, as other successful robot toys such as Furby [54] or the tamagotchi are designed in a similar manner.

Mediation between Collocated Users

By designing the interactive affordances of the multipresence robot system around the concept of nurturance, virtually augmented multipresence robots not only mediate between non-collocated users, but also between collocated users: any user - regardless of their location - can nurture the robot and feel the co-presence of other users through the robot's current state.

3.3.2 Interactive Play Experience

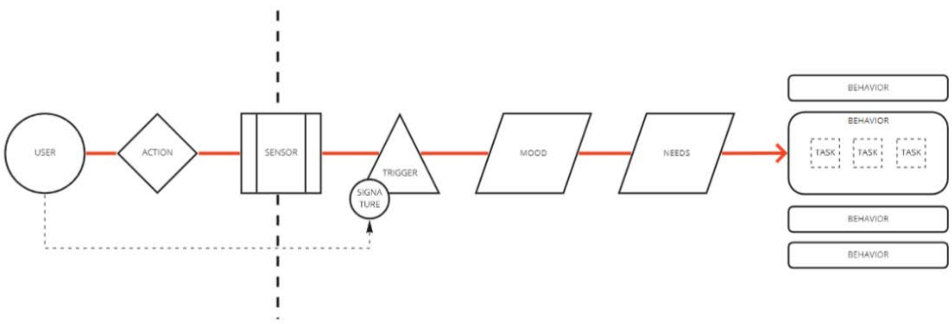


Figure 3.6 Interaction process model

We propose a process model (Figure 3.6) for an interactive play experience that is based on the concept of nurturance. We will discuss the process model from left to right: When the user performs an action, the robot's sensors will evaluate whether the action was meant to be directed at the robot. If the action is directed at the robot, the action will be recognized as an input and be converted into an object that we call ”trigger”. Each trigger is a predefined instruction that comes with a signature attached to it. The signature object is used to classify who the action was performed by. As previously explained, the multipresence robot system requires a certain degree of autonomy. The autonomy is given by a ”mood” component model and a ”needs” component model. The mood component represents the robot’s current mood (such as happy, excited, angry) while the needs component is a model of the robot’s needs (such as hunger, attention, exercise). Depending on the robot’s mood and needs, the trigger will elicit a certain behavior from the robot; each behavior is comprised of several tasks that will be executed in succession. The behavior will be replicated to all instances of the multipresence robot system. If multiple behaviors are triggered around the same time, or if a behavior is triggered while another behavior is still being executed by the system, the next behavior will be added to a queue. Behaviors will be dequeued in chronological order.

Privacy Concerns

The robot’s sensors will recognize user behavior at all times, but only directed actions will be converted into triggers (compare Figure 3.6). To alleviate privacy concerns, the user’s behavior is evaluated locally by the robot in real-time. Only the robot’s behaviors and state changes are replicated. This way, the user’s privacy is protected at all times.

3.4. Advantages of Multipresence Robot Systems

3.4.1 Mediated Ambient Telepresence

As pointed out by Jeong et al. [52], current telepresence robot systems are typically designed for one to one communication. Virtually augmented multipresence robots can establish a form of ”mediated ambient telepresence” that spans across multiple locations and can thus connect multiple users at the same time. Leveraging the affordances of physically present robots [23], our concept of ”mediated ambient telepresence” thus builds upon Madianou’s concept of ”ambient co-presence” [15].

3.4.2 Virtually Augmented Affordances

Affordances of current telepresence robots are limited. Our proposed system extends a robot's affordances by means of virtual augmentation. A wider array of affordances enables robots to mediate interactions more effectively, allowing for more meaningful - even playful - interactive experiences. Leveraging the affordances of social play [30, 32], mulitpresence robots establish a sense of ambient co-presence at all times without the need for the user to actively participate with the technology.

3.4.3 Rich Visual Feedback

Equipped with a display, virtually augmented multipresence robots can mediate between users using rich visual feedback, which is considered strongly beneficial for creating a sense of co-presence [16, 28, 29, 42].

3.4.4 Privacy

Privacy is a recurring issue in current telepresence technologies [28, 29, 52]. In any given location, virtually augmented multipresence robots will only mediate interactions that are directed towards them. Any sensory information will be evaluated locally, so that only the robot movements are being replicated and no private video or audio data is shared. As such, multipresence robots can co-inhabit an interlocutor's space without privacy concerns while simultaneously providing the benefits of mediated ambient telepresence.

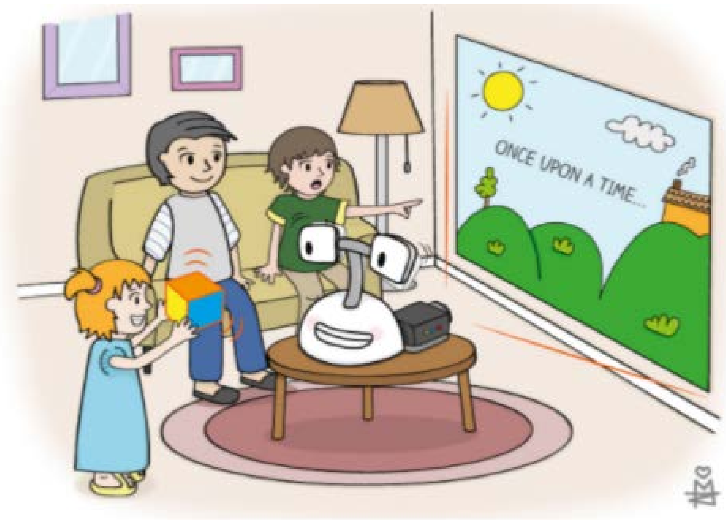
Chapter 4
Implementation

4.1. Haru

4.1.1 A Stationary Social Robot

Figure 4.1 Stationary social robot Haru

Haru [65] is a stationary social robot currently in development by Honda Research Institute (HRI) Japan (see Figure 4.1). Haru is primarily designed to communicate emotive affordances. The robot is controlled by five actuators which allow for rich emotive movements. Haru's eyes are rendered on high resolution LCD panels. The robot's mouth is displayed on a low resolution LED matrix that contrasts its high resolution LCD panels. Combining the affordances of the actuators, LCD panels and the LED matrix allow Haru to communicate a wide array



(Source: Meet Haru, the Unassuming Big-Eyed Robot [64])

Figure 4.2 Concept sketch - Haru inside a living room

of facial expressions. Furthermore, the stationary robot is connected to a large screen - a digital extension of Haru. The screen is operated by Haru, enabling the robot to communicate visual information via a graphical user interface alongside its emotive motions. Besides visual information and emotive movements, Haru also has a speech module that allows the robot to generate voices and sounds. A social robot, Haru is designed to be placed in private homes (compare Figure 4.2).

Limitations

A stationary robot, Haru's physical presence is limited due to not having any spatial agency. This can be considered a disadvantage when compared to other social robots such as the previously discussed Ohmni robot.

4.1.2 Robot Operating System

Haru is operated by the open source Robot Operating System (ROS) [1]. Processes in ROS are called "nodes"; nodes communicate with each other through data structures which are called "messages". Typically, messages are routed through what is called a "topic". In the context of ROS, topics can be understood as identifiers for certain behaviors. For example, in the case of Haru there might be a topic for moving a particular actuator or displaying content on the attached display. When a node sends a message to a topic, we call this "publishing". When a node listens to a topic, we call this "subscribing". To give an example: if we wanted to rotate the actuator inside Haru's base, we would need to publish a message to the corresponding node.

4.1.3 Routines

As a result of how ROS processes data, Haru executes behaviors (compare Figure 3.6) in the form of routines. Each routine contains an array of steps, which in return contain an array of commands. Each command is an instruction for Haru (e.g., move the base joint to a position, play a video file in Haru's eye LCDs etc.). We developed a functionally identical routine class for the virtual simulation in Unity, which allows us to seamlessly convert routines between the robot Haru and its virtual simulation. The routine class has a constructor that takes 5 arguments:

- Routine ID (int)
- Routine Name (string)
- Priority (float)
- Should loop (bool)
- Steps (Step[])

1 https://www.ros.org/

Step

Each routine contains an array of the Step type. The Step class has a constructor that takes two arguments:

- Step time (float)
- Commands (Command[])

Command

Commands are instructions for Haru to execute - they correlate to the "Task" object described in Figure 3.6. There are various types of commands which all inherit from the Command base class.

4.2. Haru as a Virtually Augmented Multipresence Robot

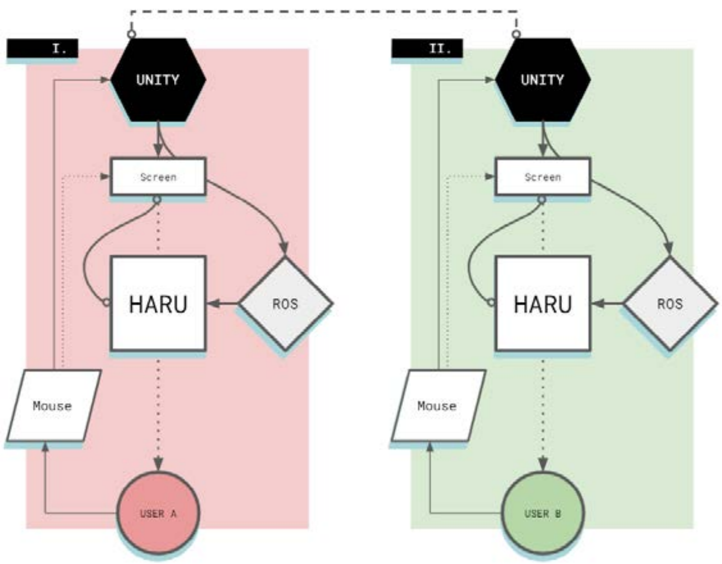


Figure 4.3 Virtually augmented multipresence robot system

We demonstrate an implementation of the virtually augmented multipresence robot system at the example of Haru. The virtually augmented multipresence robot is implemented on top of Haru's existing architecture. As depicted in Figure 4.3, the system is designed to connect two non-collocated users A and B. As explained before, Haru is connected to a screen that displays a graphical user interface. For the purpose of the virtually augmented multipresence robot prototype, the screen instead displays a virtual environment that is simulated in real time by the simulation engine Unity. The interaction model (compare Figure 3.6) is implemented in Unity. If a behavior is triggered, Unity will publish a message to the corresponding topic on the ROS server via a bash script. The robot Haru then receives the message via ROS and executes the desired behavior. In our proof of concept implementation, the user interacts with Haru using a mouse that is connected to the computer running Haru. By clicking buttons that are rendered on top of the virtual simulation, the user can trigger certain behaviors, e.g. instruct Haru to turn left or right. The set ups in location I and II are connected via a local network. Hereby, all the network communication is handled by a network manager object inside Unity. Calls to the corresponding ROS servers are replicated between the locations to ensure that both instances of the robot are in the same state at all times.

4.3. Unity Simulation

4.3.1 Virtual Twin

In order to integrate the virtual environment with the physical robot, a virtual twin [61] of Haru was developed inside the simulation engine Unity using C on a system running Ubuntu 18.04 LTS. The virtual twin serves two purposes: It communicates with other virtual twins in the multipresence system to ensure all robots are properly replicated, and it controls how the virtual environment to the back of Haru is displayed (Figure 4.4). The virtual twin is a functionally identical copy of the physical robot and can be controlled using the same routine format. The Unity simulation is controlled by various manager classes. Some of which we will discuss hereafter. Code examples can be found in the appendix.

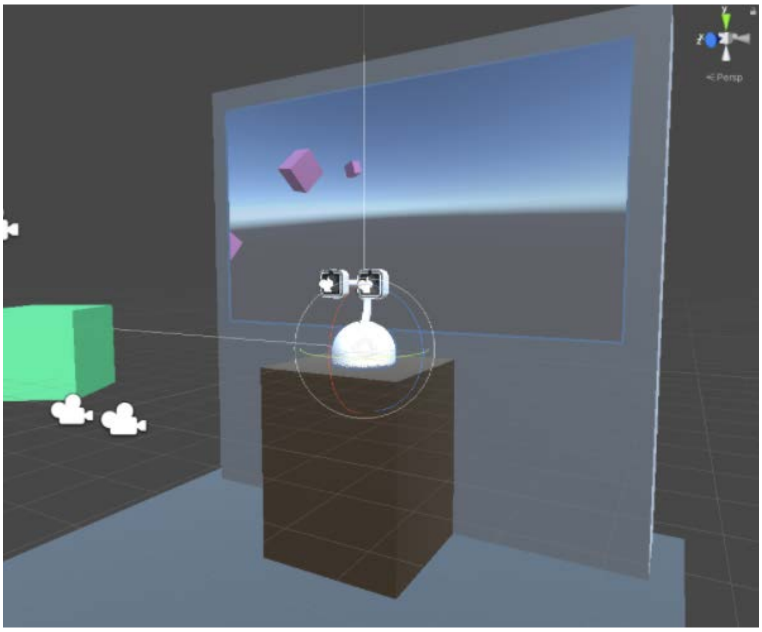


Figure 4.4 Haru's virtual twin in Unity

Application Manager

The application manager is a singleton that stores references to all other managers in the scene. Some scripts that require co routines but do not inherit from the Mono Behavior class depend on the application manager.

Camera Manager

Haru has three separate video outputs: left eye LCD, right eye LCD and the attached display (here named "projector"). Inside Unity, each of these outputs is assigned an individual render layer, which are then rendered by individual camera objects. This workflow allows us to make changes on the virtual twin and the virtual environment independently. As can be seen in Figure 4.4, the virtual twin also contains a virtual display that is controlled in the same manner as the physical display.

Input Manager

All user inputs are being registered in the input manager. The idea is that for each registered input, a static event is fired that then other classes (e.g. a custom controller) can listen to. In the case of the here discussed implementation, this pertains to mouse inputs only. However, this architecture can be expanded to include other inputs such as voice or body gestures.

Haru Manager

The haru manager class is a virtual representation of Haru and modeled in the same way as the physical robot. As such, the haru manager contains the logic for Haru's virtual twin. It receives routines from the ROS manager and executes them in the same way that the physical Haru does. The haru manager class is a networked object and thus replicated over all instances of the virtual world.

Virtual Haru Manager

The virtual haru manager inherits from haru manager. Virtual haru manager contains additional logic: The virtual environments affords Haru's virtual twin to perform actions that the physical Haru cannot. For example, Haru's virtual twin is able to walk in the virtual environment, while the physical Haru is stationary. Among other virtual-only behaviors, the walking logic is stored inside the virtual haru manager. Virtual-only behaviors are executed independently of routine behaviors, but they are replicated to other networked instances in the same way as routine behaviors.

ROS Manager

The ROS manager handles communication between ROS and Unity. The ROS manager is responsible for publishing routines to ROS. Routines are published to ROS via bash scripts. Launching bash scripts from within Unity to publish to ROS adds a noticeable latency (estimated 300ms - 500ms) to all communications between the two programs. While this is not an issue for the feasibility of our proof of concept prototype, better solutions should be investigated for future purposes.

4.3.2 Virtual Environment

Figure 4.5 Haru walking in the virtual environment

The virtual environment allows Haru to perform actions that it otherwise would not be able to perform in the physical space; most notably, Haru can freely walk around in the virtual environment (see Figure 4.5). The virtual environment has undergone several iterations which will be discussed hereafter.

2D

In the first iteration, the virtual environment was two-dimensional. However, it was quickly noted that the two dimensionality of the projection and the physicality of the robot Haru created an uncanny dissonance. A three dimensional character, Haru did not have any spatial agency in the two dimensional space. A virtual companion (a red bird, as depicted in Figure 4.6 (a)) was introduced to serve as a bridge between the virtual space and the physical Haru. This iteration of the virtual world was discarded in favor of a three dimensional space that Haru's virtual twin itself can traverse through, without having to rely on an additional virtual agent acting as a middleman.

(a) Iteration 1: 2D Environment

(b) Iteration 2: 3D Environment

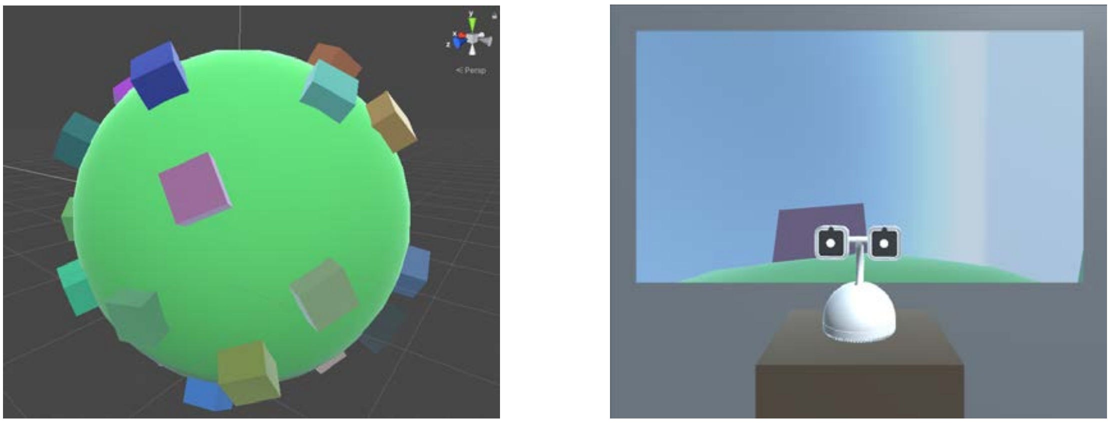
Figure 4.6 Iterations 1 and 2

3D

As can be seen in figure 4.6 (b), a virtually augmented three dimensional space proved to be a better fit for Haru. However, the limited spatial affordances of the stationary robot Haru proved to be a problem. The robot can only rotate itself by 90 degrees along the vertical axis towards either side. In order to traverse a three dimensional space, an agent needs to be able to rotate by 360 degrees along the vertical axis. Otherwise, it is not possible for the agent to reach every point in the three dimensional space. The display shows what can be seen to the back of Haru in the virtual world - because Haru cannot turn by 360, the robot cannot turn back and thus is unable to reach any of the objects that are displayed to the back of the robot.

Planet

We addressed the aforementioned traversal issue by designing the virtual environment as a small sphere - a "planet" - that the robot can move around on (see Figure 4.7). The spherical surface allows the robot to infinitely circle around the sphere, thus enabling it to reach every point of the virtual environment.



(a) Sphere

(b) Haru walking on the sphere

Figure 4.7 Iteration 3 - a spherical virtual environment

Chapter 5
Proof of Concept

5.1. Proof of Concept Prototype

Figure 5.1 Proof of concept prototype

The proof of concept prototype (see figure 5.1) consists of a walk around experience with Haru in a planet shaped virtual environment (see figure 5.2). As previously discussed, an interactive experience based on the concept of nurturance was implemented. The interactive experience is designed after the process model

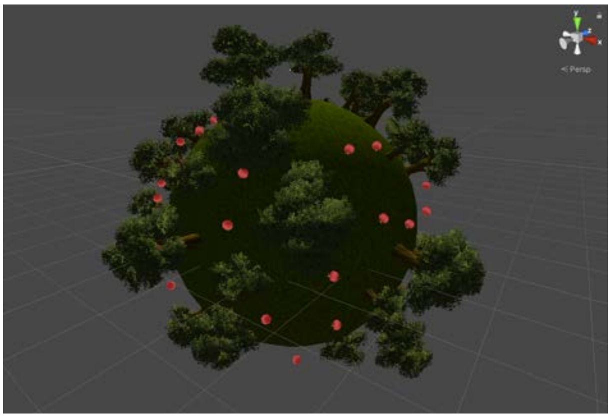
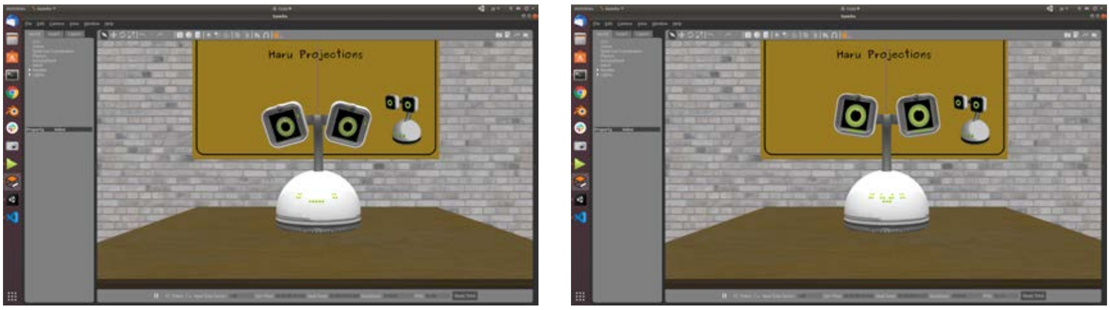


Figure 5.2 Proof of concept - virtual planet environment

(a) Screenshot 1 (b) Screenshot 2

Figure 5.3 Virtual environment as rendered in the attached display



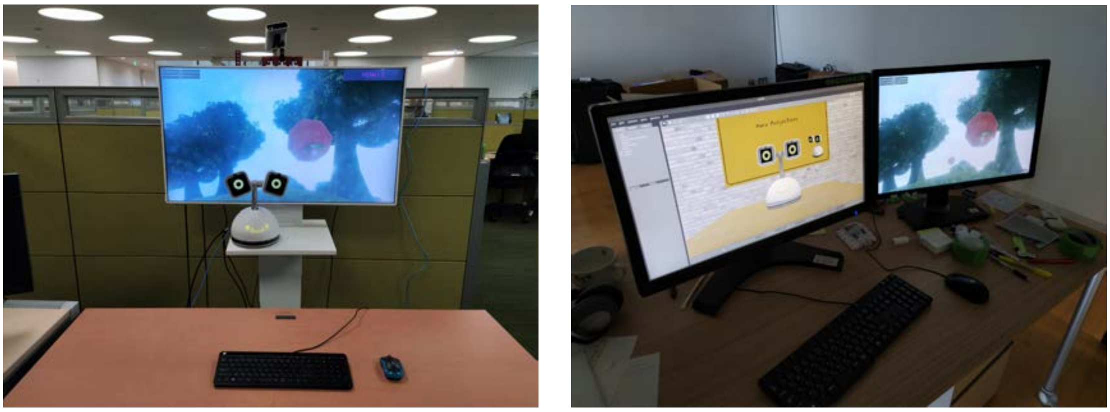
(a) Sad routine (b) Happy routine

Figure 5.4 Haru routine behaviors

that was proposed in chapter 3 (compare Figure 3.6).

Every 10 seconds, Haru's hunger increases by 20 percent. After 50 seconds, Haru signals its hunger by executing a behavior in the form of a routine animation (compare Figure 5.4, (a)). The routine animations depicted in Figure 5.4 were not designed as a part of this project, but already existed within Haru's architecture. A benefit of our implementation is that it allows us to reuse all content that has been previously designed for the robot Haru.

In order to feed Haru, the users must guide the robot through a virtual environment. To do so, the users can give Haru instructions by clicking on buttons (see Figure 5.3, upper left corner). From top to bottom, the instructions are: turn left, turn right, move. Guiding Haru per these instructions, the users can find floating apples (see Figure 5.3, (b)) scattered across the virtual environment. Users can feed Haru by clicking on one of the floating apples. In doing so, Haru's hunger level is set to 0 and the robot will execute a behavior (see Figure 5.4, (b)). Besides following the users' instructions, Haru also has some autonomous behaviors: Every seven seconds, the robot randomly turns left, right or moves forward.



(a) Condition A - robot (b) Condition B - gazebo simulation

Figure 5.5 Conditions A and B

5.2. Methodology

5.2.1 Hypothesis

A study was conducted to test our hypothesis: Interacting with the virtually augmented multipresence robot system can facilitate a sense of co presence between non-collocated users. In addition, it was evaluated whether the physical presence of the robot had a positive influence on the co-presence experience.

5.2.2 Study Design

To test our hypothesis, an AB test was designed. For this matter, two conditions were prepared: condition A had the user interact with a virtually augmented physical Haru (see figure 5.5, (a)), while condition B had the participant interact with a virtually augmented virtual Haru (compare figure 5.5, (b)) that was rendered inside a Gazebo [1] simulation. The Haru's in both conditions were instances of the same virtually augmented multipresence robot - their behaviors and the display outputs were designed to be identical.

The participants were divided into pairs of two, where for each pair one par-

1 http://gazebosim.org/

ticipant would interact with the physical Haru (condition A) and one participant would interact with the virtual instance (condition B). The pairs would be evenly distributed so that the number of participants interacting with the robot Haru for the first time would be equal to the number of participants interacting with the virtual simulation for the first time. Each test session would take three minutes. Before each session, the participants were instructed on how to interact with Haru. After each session, the participants were asked to fill out a quantitative questionnaire. The full questionnaire can be found in the appendix.

5.2.3 Questionnaire Design

The questionnaire is comprised of three sections. Section one is an anonymized collection of personal information (gender, age). Section two (questions 1 - 14) is a modified set of questions borrowed from the "Networked Minds Social Presence Measure" [40]. Section three (questions 15-19) is a set of questions pertaining to the interactive experience with Haru specifically. Section one was printed on its own page and collected separately from section two and three to warrant each participants' anonymity.

Networked Minds Measure of Social Presence

The networked minds measure of social presence [40] is a set of quantitative questions designed to evaluate technology mediated one to one communication for co-presence. The questions from the sets for first order co-presence and perceived behavioral interdependence were borrowed and slightly modified for the questionnaire. Other questions from the networked minds measure of social presence were discarded, since they were not applicable to our proof of concept, which is specifically designed to facilitate a form of ambient co-presence among participants.

Questions Pertaining to Haru

In addition to the above mentioned questions for evaluating co presence, five quantitative questions (Likert 1-5) pertaining to the experience of interacting with Haru were included in the questionnaire.

5.3. Results

All participants (N = 5) were employees working at Honda Research Institute. Four participants were male, one female. The participants' age was between 20 and 50 years. The 5 participants were divided into 4 pairs AB, BC, DE, EA. For each pair, one participant would interact with the physical Haru while the other would interact with the virtual Haru. A total of eight questionnaires with 19 items each were collected and evaluated as part of the study. The results from group A (interaction with the physical Haru) were then compared to the results from group B (interaction with the virtual Haru). For the results of the networked minds social presence inventory (questions 1-14), please refer to Table 5.1. For a comparison of the mean results from the third part of the questionnaire (questions 15-19), please refer to Table 5.2.

5.4. Discussion

5.4.1 Co-Presence Questionnaire

As can be seen in Table 5.1, participants in the virtual control group were more aware of their partner in the room (M = 3,5) than participants interacting with the physical Haru (M = 2,75). Participants from the physical control group were less likely to notice their partner in the room (M = 3,25) than participants interacting with the virtual Haru (M = 2). Participants interacting with the robot Haru were also less likely to notice their partner in the room (M = 2), whereas participants in the virtual control group were more likely to notice their partners in the room (M = 3,5). Participants in the virtual control group were more likely to say that Haru appeared to have its own mind (M = 3,5) than participants interacting with the robot (M = 2,75) and they felt more responsible for taking care of Haru (M = 4) than participants interacting with the physical Haru (M = 2,75).

Interestingly, these findings suggest that the overall experience of interacting with the virtual simulation might have been more meaningful than the interaction with the physical robot. The mean results from the first order co-presence section (first four questions) were 3 and 2,937 respectively. These results suggest that there was no strongly observable difference in the co-presence experience between

Table 5.1 Networked Minds Social Presence Inventory, mean results

Question	A	B
I often felt as if my partner and I were in the same room together	3.25	3.0
I was often aware of my partner in the room	2.75	3.5
I hardly noticed my partner in the room	3.25	2.0
I often felt as if we were in different places rather than together in the same room	2.75	3.25
My actions were often dependent on my partner's actions.	3.0	3.0
My behavior was often in direct response to my partner's behavior	2.25	2.75
What I did often affected what my partner did	3.25	3.5
I think my partner often felt as if we were in the same room together	2.75	2.0
My partner was often aware of me in the room	3	3.5
My partner didn't notice me in the room	2	3.5
I think my partner often felt as if we were in different places rather than together in the same room	3.5	3.75
My partner's actions were often dependent on my actions	2.5	2.25
The behavior of my partner was often in direct response to my behavior	2.5	2.5
What my partner did often affected what I did	3.5	4

Table 5.2 Virtual augmentation, mean results

Question	A	B
During the experiment, it appeared as if Haru was physically present in the room	4	3.33
During the experiment, it appeared as if Haru was virtually present in the virtual environment	2.75	2.75
Haru was controlled by my partner	3	3
Haru appeared to have its own mind and acted on its own	2.75	3.5
I felt responsible for taking care of Haru	2.75	4.0

groups A and B. Indeed, a T-test showed there was no significant difference between groups A and B ($p = 0{,}149$). This is contradictory to previous studies in this field [23] that suggest interacting with physically present agents evokes more positive responses from participants than interacting with virtual characters. F tests were performed for each pair AB, BC, DE, EA. The mean in-pair variance was 1,6572, which is higher than the variance of the mean results from group A and B (= 1,4235). Since the variance within pairs was higher than the variance between physical and virtual conditions, we conclude that personal preferences had a stronger influence on the experience than either of the conditions.

5.4.2 Limitations

The sample size for this study was small (N=5). Due to the COVID-19 pandemic and the Haru research project being under a non disclosure agreement, it was only possible to conduct the study with employees from Honda Research Institute Japan at this time. There were some technical difficulties during the experiment: the virtual apples did not replicate properly and the robot Haru did not play any routines to signal hunger or satisfaction. Furthermore, the robot's left eye LCD broke during one of the sessions. This certainly influenced the participants' experience. We suggest that a field trial with a larger sample size is required to provide a conclusive evaluation for our proof of concept prototype.

5.4.3 Anecdotal Evidence

Despite the inconclusive results from the quantitative questionnaire, most of the participants made favorable remarks about the multipresence robot concept after the experiment sessions. After the session, two participants mentioned how they could feel each others presence through how Haru reacted to their partner's input. This suggests that further research and development in this domain is warranted.

Chapter 6
Conclusion

Loneliness is an increasing health concern in the developed countries. While both the elderly and younger generations suffer from loneliness, the rates of loneliness are on the rise especially among Millenials and Generation Z. Current communication technologies such as SNS fail to address this issue. Counterintuitively, recent studies suggest that social media exposure may contribute to the subjective feeling of loneliness.

Social games with rich visual feedback might alleviate the feeling of loneliness, but research on this subject matter is still scarce. Besides social games, we observe a trend in telepresence robots becoming more ubiquitous in our everyday lives. Research suggests that mobile robotic telepresence systems can successfully facilitate a sense of co-presence. However, we identify several problems with current mobile robotic telepresence systems: they are primarily designed for one to one communication, the continuous transmission of audio and video raises privacy concerns and the robots are restrained by a limited set of affordances.

To address the issues of current telepresence robots, we propose a new type of robots: virtually augmented multipresence robots. Virtually augmented multipresence robots facilitate a form of physical co-presence by mediating play between two or more non-collocated users. Existing in multiple physical spaces at the same time, virtually augmented multipresence robots act as mediators between remote locations. Leveraging on Industry 4.0 technologies, our proposed multipresence robot system is comprised of a set of distributed physical robots which are virtually enhanced through an attached display that renders a virtual environment to the back of the robot. With their presence extended into a virtual environment, virtually augmented multipresence robots can perform tasks that non-virtually augmented robots cannot. For example, the virtual augmentation can allow stationary robots to walk, swim or even fly at the intersection of the material and the virtual world. Various designs for virtual environments were discussed that can accommodate for the otherwise limited affordances of stationary robots.

We implement a proof of concept prototype for virtually augmented multi-presence robots at the example of Haru - a stationary social robot currently in development by Honda Research Institute Japan. The proof of concept prototype virtually augments the robot Haru's affordances in a way that allows the stationary robot to walk in the virtual environment. Based on this technique, a playful experience was designed that allows users to explore the virtual environment together with Haru.

Our hypothesis that the virtually augmented multipresence proof of concept prototype can facilitate a sense of co-presence between non-collocated users was tested in an AB study (N = 5). Pairs of two would interact with the virtually augmented robot Haru (condition A) and a virtually augmented virtual twin of Haru (condition B) simultaneously in sessions of three minutes each. The participants - all employees of Honda Research Institute Japan - were asked to fill out a questionnaire after each session. Besides custom questions pertaining to the perception of Haru specifically, the questionnaire was comprised of modified questions from the networked minds social presence measure.

While no significant evidence was found between groups A and B, anecdotal evidence from the participants suggests that the proposed concept might have the potential to facilitate co-presence if technical issues are alleviated. We conclude that a field trial with a higher sample size is necessary to prove our hypothesis.

As of writing this, we are developing an iPad compatible version of Haru's virtual twin in Unity (see Figure 6.1). The iPad application is designed for use in future field studies with Haru. Since there was no strong observable difference between the physical and virtual condition in our pilot study, we propose to conduct a larger field trial using the iPad application as a next step. At the same time, we will continue to explore new ways in which Haru's affordances can be enhanced through the virtual augmentation.

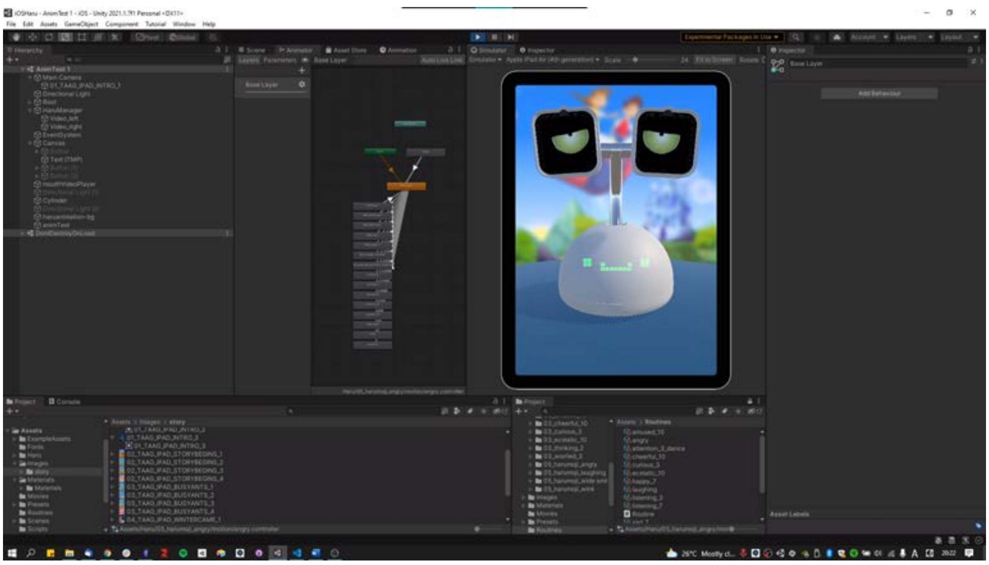


Figure 6.1 iPad application

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Appendices

A. Virtual Twin - Code Example

Internally, Haru's virtual twin processess routines from ROS as "HaruActions" in a custom state machine. The following is a code snippet of how the instructions are processed inside the virtual twin when a routine command is received by ROS.

```
namespace Haru
{
    public enum HaruActionState
    {
        Started,
        Finished
    }

    public class HaruAction
    {
        protected HaruActionState haruActionState;
        public virtual HaruActionState HaruActionState
        {
            get
            {
                return haruActionState;
            }

            set
            {
                switch(value)
                {
```

```
                case(HaruActionState.Started):
                actionStarted?.Invoke();
                break;
                case(HaruActionState.Finished):
                actionFinished?.Invoke(this);
                break;
            }
        }
    }

    public delegate void OnActionStarted();
    public OnActionStarted actionStarted;
    public delegate void OnActionFinished(HaruAction haruAction);
    public OnActionFinished actionFinished;

    public virtual void Execute()
    {
        HaruActionState = HaruActionState.Started;
    }

    public virtual void Update(HaruAction haruAction)
    {

    }

    public virtual void Finish(HaruAction haruAction)
    {
        HaruActionState = HaruActionState.Finished;
    }
}

public class HaruCommandAction : HaruAction
{
```

```
        protected MotorCommand motorCommand;
        protected Transform joint;
    }

    public class HaruMotorCommandAction : HaruCommandAction
    {

    }
}
```

B. Haru Action - Code Example

As an example, this implementation of the "Haru Roll Base Action" contains the instructions for moving the base actuator inside Haru.

```
public class RollBaseAction : HaruMotorCommandAction
    {
        public RollBaseAction(MotorCommand _motorCommand, Transform _joint)
        {
            motorCommand = _motorCommand;
            joint = _joint;
        }

        public override void Execute()
        {
            MonoBehaviour.print("Roll Base Action Start");

            base.Execute();
            ApplicationManager.Instance.StartCoroutine(RollBase());
        }

        private IEnumerator RollBase()
```

```
{
    var t = 0f;

    var playTime = motorCommand.PlayTime / 100f;

    var startPos = joint.eulerAngles.y;

    var targetPos = motorCommand.Pos.ROSRADToUnityDEG();

    var deltaPos = 0f;
    if(IsSimpleInterpolation(startPos, targetPos))
    {
        while(t < 1f)
        {
            deltaPos = Mathf.LerpAngle(startPos, targetPos, t);
            joint.rotation = Quaternion.Euler(joint.rotation.x,
            deltaPos, joint.rotation.z);
            t += Time.deltaTime / playTime;
            yield return new WaitForEndOfFrame();
        }
    }
    else
    {
        float distanceA;
        float distanceB;

        if(startPos > 180f)
        {
            distanceA = 360 - startPos;
        }
        else
        {
            distanceA = startPos;
```

```
        }

        if(targetPos > 180f)
        {
            distanceB = 360 - targetPos;
        }
        else
        {
            distanceB = targetPos;
        }

        var playTimeStep = playTime/ (distanceA + distanceB);

        while(t < 1f)
        {
            deltaPos = Mathf.LerpAngle(startPos, 0f, t);
            joint.rotation = Quaternion.Euler(joint.rotation.x,
            deltaPos, joint.rotation.z);
            t += Time.deltaTime / (playTimeStep * distanceA);
            yield return new WaitForEndOfFrame();
        }

        t = 0f;

        while(t < 1f)
        {
            deltaPos = Mathf.LerpAngle(0f, targetPos, t);
            joint.rotation = Quaternion.Euler(joint.rotation.x,
            deltaPos, joint.rotation.z);
            t += Time.deltaTime / (playTimeStep * distanceB);
            yield return new WaitForEndOfFrame();
        }
    }
```

```
            Finish(this);
        }

        private bool IsSimpleInterpolation(float startPos, float targetPos)
        {
            var cond1 = startPos <= Constraints.BaseRoll_max &&
            targetPos <= Constraints.BaseRoll_max;
            var cond2 = startPos >= Constraints.BaseRoll_min &&
            targetPos >= Constraints.BaseRoll_min;

            if(startPos == 0f || targetPos == 0f)
            {
                return true;
            }
            else if(cond1 || cond2)
            {
                return true;
            }
            else
            {
                return false;
            }
        }

        public override void Finish(HaruAction haruAction)
        {
            base.Finish(this);

            MonoBehaviour.print("Base Roll Action Finished");
        }
    }
```

C. Proof of Concept Evaluation Questionnaire

Gender

☐ Female ☐ Male ☐ Other: ________

☐ Prefer not to say

Age

☐ 0 - 10 ☐ 10 - 20 ☐ 20 - 30 ☐ 30 - 40 ☐ 40 - 50 ☐ 50 - 60 ☐ 60 +

Figure C.1 Questionnaire Page 1

I often felt as if my partner and I were in the same room together.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

I was often aware of my partner in the room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

I hardly noticed my partner in the room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

I often felt as if we were in different places rather than together in the same room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

My actions were often dependent on my partner's actions.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

My behavior was often in direct response to my partner's behavior.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

What I did often affected what my partner did.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

ID: __ Condition: ☐ Virtual
Partner ID: __ ☐ Physical

Figure C.2 Questionnaire Page 2

I think my partner often felt as if we were in the same room together.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

My partner was often aware of me in the room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

My partner didn't notice me in the room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

I think my partner often felt as if we were in different places rather than together in the same room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

My partner's actions were often dependent on my actions

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

The behavior of my partner was often in direct response to my behavior.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

What my partner did often affected what I did.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

ID: __ Condition: ☐ Virtual
Partner ID: __ ☐ Physical

Figure C.3 Questionnaire Page 3

During the experiment, it appeared as if Haru was physically present in the room.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

During the experiment, it appeared as if Haru was virtually present in the virtual environment.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

Haru was controlled by my partner.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

Haru appeared to have its own mind and acted on its own.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

I felt responsible for taking care of Haru.

Strong Disagree	Disagree	Neutral	Agree	Strong Agree
☐	☐	☐	☐	☐

ID: __ Condition: ☐ Virtual
Partner ID: __ ☐ Physical

Figure C.4 Questionnaire Page 4