Sharing Spaces with Robots
An Integrated Environment for Human-Robot Interaction

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ABSTRACT

In this paper we offer an intelligent integrated environment for human-robot interaction. This environment takes advantage of the fact that robots are both digital and physical entities, thus improving human-robot interaction and communication. Using mixed reality, our approach brings digital information directly into the physical environment, allowing users to interact with robots' ideas and thoughts directly within the shared physical interaction space. We also present a taxonomy which we use to organise and classify the various interaction techniques that this environment offers. Using this taxonomy, we demonstrate by detailing three interaction techniques, *thought crumbs*, *decorations* and *bubblegrams*. To evaluate these techniques, we offer the design of a realisable prototype.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Input Devices and Strategies, Interaction Styles*; I.3.6 [**Computer Graphics**]: Methodology and Techniques —*Interaction Techniques*; H.1.2 [**Models and Principles**]: User/Machine Systems—*Human Factors*

Keywords

Intelligent Environment, Mixed Reality, Human-Robot Interaction, Human-Computer Interaction

1. SCENARIO

A futuristic human and robot collaborative search and rescue team has been dispatched to assist in a situation concerning a burning apartment building. En route, the robot team members analyse a map of the burning building, calculating things such as potential danger areas, likely civilian locations, and efficient ways to distribute the team throughout the building. At the same time, the human team members prepare and put on their protective gear, including a helmet which has mixed reality capability. This capability is used to augment the vision and hearing of the human team members with information from the robot team members.

As the team enters the building, the humans quickly follow highlighted mixed reality paths representing the robots' suggested routes. As the search progresses, additional highlighted paths are created, representing which route each robot has taken. If a robot hits an obstructed door or encounters dangerous heat levels, it attaches mixed reality icons to the environment, placing a locked *icon on the door or* heat *symbols on the walls. Human members who later come the same way see these icons and use the information to make decisions. When human and robot team members meet, the robot pops up a mixed reality menu interface to show its current status and to ask for further instructions.*

2. INTRODUCTION

Robot technology is advancing steadily, and many people believe that, similar to the computer revolution over the last few decades, a robotics revolution is upon us [11, 13]. Indeed, Norman [13] suggests that we are already surrounded by robots, such as computerised dishwashers and cars, but they currently lack the intelligence and capability required for us to see them as such. As robots become increasingly intelligent and capable, we will find ourselves sharing our environment with them in many ways. As such, it is important that we understand the various issues and problems surrounding interaction with robots and develop effective interfaces to work with them. This field of study is called *Human-Robot Interaction* (HRI) [8].

Robots are a class of computers which are distinguished by their presence in the physical world. Unlike a conventional computer which is primarily a digital entity, a robot is both a physical and a digital entity, simultaneously perceiving, functioning and interacting in both the digital and physical realms. Current human-robot interfaces often fail to acknowledge this, and are commonly designed using physical modalities such as speech-based interfaces or digital modalities such as remote control software tools. This separation of interaction spaces can hinder communication between humans and robots, resulting in various interaction problems such as limitations in conveying information or inefficiencies due to issues in input/output unification [4, 18].

One solution to this problem is to use *mixed reality* (MR) as an interaction paradigm. MR is a technique which tracks components of the physical world and augments them with useful computer data. This is commonly accomplished by projecting augmented images onto the user's environment or by using a head-mounted display (HMD) to synthetically augment the vision of the wearer [1]. We believe that MR solves the human-robot interaction problems mentioned above by allowing the robot to superimpose digital information directly onto the physical environment, allowing a human user to interact with the digital information directly within their physical interaction space. Combining the physical and MR interaction spaces, we have devised an intelligent environment which the humans and robots can use to interact. We call this shared environment the MR Integrated Environment (MRIE)[1].

Given that robots are generally autonomous and mobile, they have a very large and dynamic physical interaction space. With the MRIE, we offer an environment which allows robots to utilise this space both physically and digitally, using the entire physical environment as their digital interaction space. The result of this is an extremely flexible interaction environment which robots can use to express their digital ideas and thoughts. We believe that this environment also aids in increasing a human's awareness of the robot, which some researchers claim improves understanding of the robot's location, identities, and activities [20].

There is a wide range of potential human-robot interaction techniques within the MRIE. As a method of organising this, we introduce a taxonomy of the MRIE which we use to analyse, classify, and compare various MRIE interaction techniques. This taxonomy maps the MRIE into four variables: *virtuality*, *lifespan*, *ownership*, and *activity*. We also introduce the *interaction field*, a concept where each variable of the taxonomy represents an axis in a four dimensional field of interaction techniques. To demonstrate the application of this taxonomy and to show how various techniques fit into the *interaction field*, three MRIE interaction techniques (*thought crumbs*, *decorations*, and *bubblegrams*) are presented. Furthermore, we detail the design for a preliminary prototype which will be able to realise and evaluate the ideas and techniques presented here.

3. RELATED WORK

Mixed reality (MR) has been used as a means of combining digital information with the physical world for various applications, including animating storybooks(the *MagicBook* project) [1], controlling robots [4, 9, 14, 17], modelling volumetric data [7, 16], and assisting with medical surgery [5]. Work by Ramesh et al. has also discussed using MR to create an integrated environment (shared between humans) rather than particular techniques [15].

From a simple perspective, most MR techniques can be classified as either using head-mounted-display (HMD) visualisation or projective visualisation. HMD visualisation offers portability and flexibility, given that they are often light weight and can be connected to a wearable computer, and that they can display anywhere within the user's vision. However, HMDs often constrict the user's vision due to a poor field-of-view and low resolution, resulting in hand-eye coordination issues and possibly motion sickness. Projective visualisation, on the other hand, can be integrated seamlessly into a user's entire field of view, allowing the user to use the full capabilities of their natural vision. The downside, however, is that projectors are generally less portable and flexible than HMDs, as projectors are often heavy and difficult to move and they require a projection surface and appropriate lighting.

As shown here, MR offers a wide range of interaction techniques and ideas. To organise this range, there has been work on describing, organising, and mapping the diverse MR interaction space. Milgram and Kishino map MR interaction to a set of criteria which is visualised on the *virtuality continuum* [10], a one dimensional axis which classifies systems as somewhere between the pure physical environment and a complete virtual environment. Others have expanded on the *virtuality continuum*, such as Dubois et al. who covers the entire continuum, offering a clear mechanism for discussing interaction techniques [2]. The *virtuality continuum* provides a mechanism for classifying MR systems and techniques. For example, the *MagicBook* project mentioned above used this as motivation and to explain the various interaction techniques integrated into the system [1].

The literature offers various taxonomies, including ones that target general human-computer interaction [12], and ones that are more HRI-specific [3]. For example, Yanco and Drury offer a taxonomy for multi-robot systems which uses task type and criticality for classification [20].

While *mixed reality* has been used for various interaction applications, there has been a limited amount of work using *mixed reality* for human-robot interaction (HRI). In relation to this work, our MRIE is unique in that it offers an integrated digital and physical environment to be shared between humans and autonomous robots. We also offer a taxonomy for the MRIE, similar to other taxonomies offered, and the concept of the *interaction field*. The *interaction field* builds on Milgram's *virtuality continuum*, providing a multi-dimensional mechanism for classifying MRIE interaction techniques; the *virtuality continuum* is simply a single axis within our four-dimensional *interaction field*, which we present later. Just as Milgram's *taxonomy of mixed reality* and *virtuality continuum* offer a clear way to analyse, classify, and compare various MR interaction systems, our taxonomy and *interaction field* offer similar benefits for analysing MRIE interaction techniques.

Because the MRIE deals primarily with humans interacting with autonomous and mobile robots in a shared physical space, portability and flexibility are very important aspects of prototype plan. As such, our prototype plan uses HMDs for the *mixed reality* interface.

4. A TAXONOMY FOR THE MIXED REALITY INTERACTION ENVIRONMENT

Our taxonomy maps the entire interaction space of the *Mixed Reality Integrated Environment* (MRIE) into four key variables, *lifespan*, *ownership*, *activity*, and *virtuality*, providing criteria which we use to describe existing MRIE interaction techniques and to construct new ones. The MRIE provides many possibilities, where both humans and robots can create, modify, destroy, and interact with MR elements.

An interaction technique in the MRIE can be broken down into separate physical and MR components; the physical component can include instances such as touching a robot or working together with a robot to push a physical object, and the MR component can include any interaction which makes use of the *mixed reality* interaction paradigm. While our taxonomy covers all MRIE interaction techniques, our focus will be on using the taxonomy to analyse the capabilities offered by the *mixed reality* aspects.

[1]pronounced *merry*

Table 1: Summarises the ways that these techniques map to our taxonomy.

	Lifespan	Ownership	Activity	Virtuality
Bubblegrams	short term	the creating robot	highly active and interactive	medium
Thought Crumbs	variable: short or long term	public	highly active, low interactivity	medium
Decorations	persistent / long term	the creating robot	low activity, no interactivity	medium

4.1 Lifespan

The *lifespan* variable determines how long instances of a MRIE interaction technique last. For example, a robot may place a permanent MR element into the environment for information purposes, resulting in an arbitrarily long or permanent *lifespan.* On the other hand, a robot may display a surprise mark which is designed to disappear soon, resulting in a very short *lifespan. Lifespan* can also be connected to an event in the environment or a variable on the owner, so that the interaction instance ends when the event is triggered.

Another option is to have the *lifespan* tied to an event in the environment or to a variable on the owner of the instance, so that the instance ends when the event is triggered.

4.2 Ownership

The *ownership* variable determines which robot, if any, owns a technique instance; *ownership* reflects who has the control of the instance. This variable also includes partial *ownership* by other entities in the environment. For example, entities in the environment may have control to alter instances owned by a different entity. The possibilities here resemble common file system permissions, where the owner can decide which other entities can view or edit aspects of a technique instance. This allows for private interaction between two entities or a group, where entities not involved would not be able to perceive or be involved in the interaction. Instances can also have no owner, such as MR element left at a location for information purposes; any element in the public space can perceive or modify these public instances.

4.3 Activity

The *activity* variable determines how active an interaction technique instance is. This includes the level at which the instance attracts attention, in what way the the instance uses the representation techniques, as well as how it responds to attention or direct interaction. An example of a technique with very low *activity* is a MR element which displays a static decoration on a wall; this technique does not actively invite attention, and does not react to interaction attempts. A variation on this technique which uses animation or other methods to gain attention would have a higher *activity* level. An example of a technique with high *activity* is a MR interactive menu system which incorporates three dimensional animation and sounds for interaction purposes. Upon creation, this menu could make a *popping* noise to notify the user of its creation, and could react richly to a user's interaction. *Activity* may also be dependent on the *ownership* or *lifespan* variables, so that a technique instance reacts differently for different users or as it ages.

4.4 Virtuality

The *virtuality* variable is based on Milgram's *virtuality continuum* [10]; it categorises the representation technique as somewhere between purely physical and purely virtual. A purely physical technique could involve physically touching a robot and getting a physical action response, while a purely virtual technique could be to use virtual reality to control a robot. Most techniques possible in the MRIE, however, lay somewhere in the middle. For example, a MR interactive menu which pops above a robots head has physical elements in that it is integrated into the physical space, and has virtual elements since the menu is presented using virtual means. Note that *virtuality* includes all forms of virtual information, including graphics and sound. An example of a technique which uses both aural and visual representations is a MR sign which visually wobbles while producing a creaking sound to show that it is loose.

4.5 Interaction Field

The *interaction field* is a conceptual representation of our taxonomy, where each variable of the taxonomy, *ownership, timespan, activity, and virtuality,* represents an axis in a four dimensional field of interaction techniques. Any MRIE interaction technique can be either a point in the field, or span a subspace of this field. The *interaction field* offers a four-dimensional representation of our taxonomy, very much like how Milgram's one-dimensional *virtuality continuum* offers a representation of his *taxonomy of mixed reality.*

5. INTERACTION TECHNIQUES

The MR Integrated Environment (MRIE) provides a flexible interaction environment between humans and robots which can be used to simultaneously interact in the digital and physical realms. Within this environment, the various interaction techniques can be described using our taxonomy of the MRIE. This section illustrates both the possibilities of the MRIE interaction space and the use of our taxonomy by introducing and discussing example interaction techniques.

There is a large number of possible interaction techniques in the MRIE. This section presents three different techniques, illustrating how the MRIE can be used, and how techniques can be described using our taxonomy. These techniques are *bubblegrams*, *thought crumbs*, and *decorations.* Table 1 summarises the way these techniques map to the taxonomy.

5.1 Bubblegrams

Bubblegrams are MRIE interaction techniques based on comic style thought and speech bubbles, with the idea that they represent a robot's thoughts and expressions (see Figure 1). They are primarily visual interfaces which use MR to overlay the bubbles onto the physical interaction scene, floating next to the robot which generated it. *Bubblegrams* can also be interactive, offering interfaces such as status displays or system menus, resembling an interactive physical display directly within the physical task space.

Lifespan: *Bubblegrams* are designed for short-term and specific interaction, and are generally not used for long-term tasks; they are designed to convey current information or for immediate interaction. For example, a surprise *bubblegram* floating over a robot's head may last for five seconds, and a system menu *bubblegram* will be destroyed as soon as the interaction is complete.

Ownership: Following the comic-style bubble motivation, *bubblegrams* are represented as being spatially attached to the owner in the MRIE interaction space. Furthermore, *bubblegrams* are used to represent a single robot's thoughts and expressions, and so *bubblegrams* must have a single owner.

Activity: While interactivity is not implied by the thought bubble motivation, *bubblegrams* offer a wide range of *activity*, ranging from a static graphic with no interactivity to a full-fledged animated and interactive menu. A static graphic could be a robot displaying a cloud emblem over its head to indicate that it is depressed, and a highly interactive menu could be a web browser interface. Highly interactive *bubblegrams* can provide a wide range of data, ranging from email messages to video or picture data.

Activity of the *bubblegram* may change throughout time as well, such as starting out by *popping* into a user's environment but becoming static after that.

Virtuality: *Bubblegrams* have medium virtuality, since they can actively bring complex digital data into the user's interaction space. For example, a fully-interactive and animated *bubblegram* menu has medium *virtuality* because it brings a vast range of information including videos and audio into the user's interaction space and allows the user to directly interact with the virtual space.

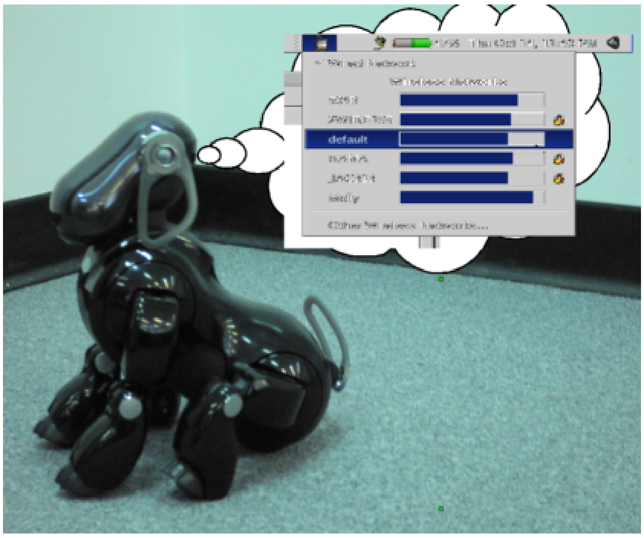

Figure 1: An artistic rendition of a *bubblegram*.

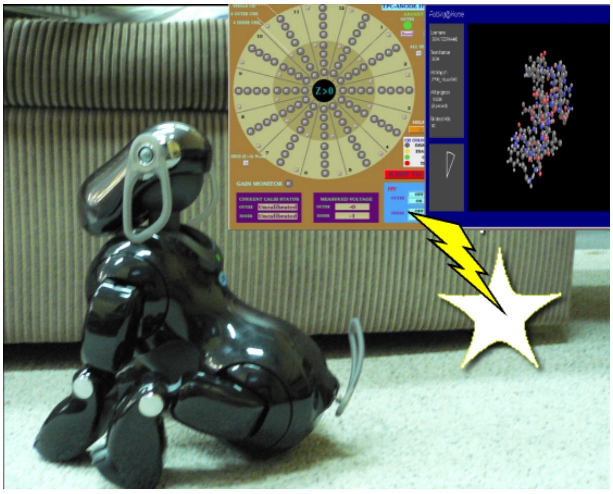

Figure 2: An artistic rendition of a *thought crumb*.

5.2 Thought Crumbs

Thought crumbs, inspired by bread crumbs from the children's story Hansel and Gretel, is an interaction technique which uses pieces of digital information to represent a robot's thoughts or observations (see Figure 2). These are pieces of digital information which an entity leaves behind in the MRIE by virtually attaching them to specific physical locations. These *thought crumbs* are then represented by a MR element, consisting of visual and/or audio augmentation, at that particular location. For example, search and rescue robots may use *thought crumbs* to leave information such as air quality and temperature levels at particular locations. *Thought crumbs* can also be interactive, such as expanding when a user touches them to give additional information.

While we see *thought crumbs* as a technique to be used by robots, we acknowledge that they can sometimes also be used by human users; for example, a human may want to mark particular locations for a cleaning robot to clean.

Lifespan: *Thought crumbs* can have any length of *lifespan* that the robot wants, depending on how long the owner thinks the information is relevant. Some *thought crumbs* will be given a period of time after which they will expire, while others will not expire until someone explicitly erases them. A short-lived *thought crumb* may be a note left by a cleaning robot after cleaning a floor to say that the floor is wet; this thought crumb would expire after approximately ten minutes. A long term *thought crumb* could be a set of directional arrows left by a robot to direct a flow of traffic. These arrows would possibly be left until explicitly destroyed, possibly weeks later.

Ownership: *Thought crumbs*, once placed, are public elements within the shared environment and have no owner. Being an independent MR element, any entity within the space has full access to modify or destroy it. This fits many of the examples already presented, as a cleaning robot may destroy *thought crumbs* which a human placed asking it to clean, or a human may remove *thought crumb* notes left behind by a cleaning robot.

Activity: *Thought crumbs* generally offer little to medium *activity*. The concept of a *thought crumb* is to represent basic ideas and information which a robot in the space wishes to attach to a location. As soon as the information which a robot wishes to leave at a location becomes complex or highly interactive, then *thought crumbs* are no longer applicable and another interaction technique should be used. Interactive *thought crumbs* should only use the interaction to give basic expansions on the data already presented. An example of an interactive *thought crumb* could be a box which displays a bit of text, with scroll bars on the side to scroll through the text.

Thought crumbs can use a full range of representation techniques to convey their information, including three dimensional animated graphics and sound. This representation technique can be used to increase the *activity* of the *thought crumb*, trying to get the users attention. For example, in an emergency situation a *thought crumb* may emit a siren noise and flash bright colours. This representation can also be dependent on the age of the thought crumb, such that the age is conveyed to human users. For example, an old thought crumb may look wrinkled, faded, or rusty.

Virtuality: *Thought crumbs* have medium *virtuality*, as they actively use the virtual techniques to convey information. For example, a *thought crumb* may use flashing lights and animation to attempt to get a user's attention.

5.3 Decorations

A *decoration* is an interaction technique which a robot uses to decorate the MRIE, virtually attaching MR *decorations* to physical locations (see Figure 3). These *decorations* are intended to be personal, artistic, and relatively permanent within the MRIE. *Decorations* can be used for placing MR paintings on a wall or to overlay patterns on an environment. For example, a robot may place its favourite snapshots on a wall and decorate a room based on some observations that it found interesting. A human user could then view this space, getting insight into the personality of the robot. *Decorations* are primarily for an entity's own expression, as they are designed for personalisation.

Lifespan: *Decorations* are persistent MR elements which do not have a specified lifetime. This means that they exist until explicitly destroyed by the owner. This is because *decorations* are not likely to change relatively fast, and by their very nature they are intended to be static.

Ownership: *Decorations* are owned solely by the robot creator, since they are personal MR elements. This means that other entities in the MRIE can not edit or destroy the *decoration*. Furthermore, the owner has full control of who views the *decoration*; some decorations may be visible by the owner only, while others may be visible by a group of friends only, or by everyone.

Activity: *Decorations* generally have low activity. They have no direct interactive properties; as the name suggests, they are designed for decorating an environment, and have no direct utility which an interaction system could take advantage of. However, decorations can use any of the representation methods available, including the full range of graphic and audio augmentation. This allows a level of flexibility in what the owner of a *decoration* can represent with it. Furthermore, the representation of the element can be dependent on variables in the owner, such as the owner's mood or how busy the robot is. For example, a portrait *decoration* may reflect the mood of the *decoration's* owner, smiling when the robot owner is happy or frowning when the robot owner is sad.

Virtuality: *Decorations* have medium *virtuality*. This is because *decorations* can use animations and graphics to bring digital information into the MRIE.

5.4 Applications

The three MRIE interaction techniques presented in this section provide a multitude of possibilities and can be used in various situations. This section is used to illustrate possible uses and to motivate the MRIE interaction space. Two application scenarios are discussed: interaction with search and rescue robots, and interaction with a household robot.

5.4.1 Search and Rescue

A variant of the scenario already presented is expressed here in terms of the three introduced interaction techniques.

Imagine a futuristic human and robot collaborative search and rescue team which uses the MRIE as a versatile and dynamic interaction environment. As the team enters a burning building, the robot team members rush ahead, surveying the building and leaving behind MR *thought crumbs*. These *thought crumbs* augment the vision of the humans, suggesting routes to take and highlighting various observations along the way. These observations include *locked* icons on doors which the robots found to be obstructed or skull and cross-bone *poison* icons representing dangerous gas levels. Finding a human survivor or victim, a robot notifies the human team members, and the humans can follow the particular robot's *thought crumbs* directly to the person.

Upon encountering a human team member, a robot can display a *bubblegram* to the human, *popping up* a MR system

Figure 3: An artistic rendition of *decorations*.

menu which can be used to get status information about the robot or to give the robot commands. Humans can also issue queries to the robot, to get information about other robots or vital signs of a survivor, and will receive live results in an active *bubblegram*. In this scenario, humans can also leave thought crumbs behind for other humans or robots. For example, a human may want to leave information to other team members, leave directions for any robot which comes their way, or to mark a spot where capable robots should bring victims and survivors.

This scenario does not use the *decorations* interaction technique because of the nature of the scenario. *Decorations* are for long-term static elements, whereas the search and rescue team will not likely frequent the same rescue locations.

5.4.2 Household Robot

Household robots exist on the market today, and with advancing technology they will likely become more popular. As such, effective HRI interaction techniques will become increasingly important.

Imagine a household robot which does cleaning and basic chores. One option for communicating with this robot is to use the MRIE, where human family members wear futuristic light weight MR glasses resembling sunglasses. Using this environment, the mother of the house can leave a *do not enter thought crumb* outside the door of her crafts-room to keep the robot out, or the father can mark areas of the garden that he would like the robot to weed. The robot also leaves thought crumbs for the humans, indicating things such as areas which were difficult to clean, or leaving an apology note beside a vase that the robot had broken during cleaning. Returning from school, the children wear the MR glasses and use a *bubblegram* menu on the robot to select which lunch they want packed for the following day. Later in the evening, while reading a book, the father verbally asks the robot to do an internet search regarding the book. Using *bubblegrams*, the robot displays the website to the father, allowing him to interact with it. This interface can be used as a portable computer, allowing human users to surf the internet, check their email, or watch a video.

A household robot also uses *decorations* around the house. These decorations represent various observations by the robot, such as favourite pictures or places. They could also be used to illustrate places that a robot does not like, such as an area where it broke something, or the top of a stairwell where it had once fallen down (idea inspired by [11]).

6. PRELIMINARY PROTOTYPE

In order to test the various ideas and techniques presented in this paper, we are developing a preliminary prototype. This section presents the details, structure, and decisions surrounding the prototype.

In order to get a working prototype which uses the MRIE, there are a few problems which need to be solved. First, we need to select appropriate MR equipment for the humans to use and a set of robots with sufficient capability to participate in the MRIE. Second, a computer vision system needs to be implemented which can identify locations in the physical space for *thought crumbs* and *decorations*, and identify robots for the *bubblegrams*. Thirdly, an interaction system must be developed which allows human users to interact with the MR elements. Finally, a shared digital space, representing the digital interaction environment of the MRIE, must be created and implemented. With these steps implemented, we will be left with a prototype which can be used to evaluate the techniques presented here.

6.1 Equipment and MR Platform

When selecting the MR equipment for the human users to use, the main selection criteria are usability and comfort. This means that in addition to being able to render MR elements, the system must be portable and comfortable, allowing the user to move around an environment and to use the system for a reasonable length of time (up to about thirty minutes). In addition to this, the system must be able to access a local network to allow communication with the robots.

As discussed in Section 3, head-mounted displays (HMDs) are well suited for this application. After surveying many available HMD models, we selected the Icuiti DV920 HMD. This model offers reasonable resolution (640×480 pixels) and is extremely light weight and portable, with the display weighing only 3.5 oz. To obtain see-through capability, we attached a modified Creative Web-cam to the front centre of the goggles. A good comparison of video see-through vs optical see-through, and motivation for video see-through, is given in [4]. To power these modified glasses, a wearable computer must be used. We decided against connecting the user to a desktop via long cables for comfort and usability reasons. For the wearable computer, we are planning on buying an *ultra-portable personal computer* (UPC) such as the Sony VGN-U50 (550 g, 167 mm×108 mm×26.4 mm, W×L×H), as this computer can be comfortably carried for extended periods of time and does not get too hot. In the meantime we are using a Toshiba tablet PC (carried in hand) to develop and evaluate the system.

For the robots, we are using Sony AIBO robot dogs. These dogs offer versatile capabilities in both the physical and digital aspects of the MRIE; they are mobile, have built-in vision systems, and have a fair amount of computational power. In addition to this, they have wireless networking capabilities, allowing them to connect to the human users.

6.2 Computer Vision

This preliminary prototype must be able to recognise landmarks for the *thought crumbs* and *decorations*, and to recognise Sony AIBOs for the *bubblegrams*. Recognition of landmarks is a different problem than recognition of AIBOs, given that the appearance of the AIBOs is known, but the vision must select unique landmarks out of an unmapped environment. Even with the AIBOs, vision is complicated by the diversity of the AIBO; it can sit, stand, fall on its side, move it's head, and display a wide variety of LED configurations. To simplify this issue for the purposes of this prototype, constraints have been added to both the landmark detection and the AIBO detection. For the unique landmarks, a test environment will be setup where the landmarks are pre-selected and physically marked using unique markers. This way, the computer vision has only to recognise the specifically-designed markers and does not have to interpret the physical space. To simplify the AIBO finding, the AIBO is restricted to a particular set of poses; the AIBO will always be standing or walking in the same pose, and will always have its lights shut off.

While stronger vision algorithms may be needed before the techniques presented in this paper can be fully realised, the current implementation is sufficient for testing purposes.

With these constraints in place, we have managed to use a single algorithm for both recognition problems. We have used the Intel OpenCV [6] library to implement and employ a technique developed by Viola and Jones, which offers rapid and robust object-detection [19]. This object detection uses computer learning methods to create classifiers for specific objects. While this has not yet been implemented for the unique location markers, this is currently implemented and working well for the detection of AIBOs.

6.3 Interaction System

Many MRIE elements allow for direct interaction with MR elements, and so a system must be implemented which allows users to do this. While this problem has not yet been solved, this problem could be approached in a variety of ways, including using three-dimensional interfaces, wand interfaces such as the one used in [4], or by incorporating computer interfaces such as a PDA or tablet PC.

6.4 Shared Digital Space

As previously described, the MRIE consists of a shared digital space integrated into the shared physical space. In order to realise this digital space, there must be a system which entities in the space can use to convey the digital information. Furthermore, this system should be always accessible from within the space, as some MRIE elements are permanent within the space.

The approach used in this prototype is to implement a central server which all entities within the space connect to for the digital interaction. Each entity can place MR entities onto the server and can view the entities on the server in relation to their location in the environment. This server provides an interface which allows entities to specify MR elements in terms of their mapping in our taxonomy, and will also offer templates to represent *bubblegrams*, *thought crumbs*, and *decorations*.

7. FUTURE WORK

This paper presented a preliminary prototype design which could be used to implement the MRIE. The immediate future work is to finish this prototype, and to utilise it for evaluation of the MRIE and the techniques presented. To evaluate the techniques, a comprehensive evaluation criteria must be developed, combining quantitative and qualitative aspects as a means to compare the effectiveness of particular techniques. From here, various user studies and experiments will be designed and implemented as a means to test the system and the evaluation criteria.

While the taxonomy presented offers a clear system for describing possible techniques in the MRIE, there is room to add depth to this taxonomy, breaking each existing category into multiple, more narrow, categories. For example, the *activity* variable could be further broken down into various aspects such as *response to interaction* and *representation technique*, and *representation technique* could be broken down into categories such as *graphical, audio*, or *haptic* representation. Furthermore, the *activity* variable could be split into *contained* and *non-contained activity*, where *contained activity* happens in the MR element and does not directly involve a user, and *non-contained activity* involves interaction with users.

We have considered the MRIE as a shared interaction environment between humans and robots. However, the MRIE allows for entity-independent MR elements, such as *thought crumbs*, to reside in the space. It would be interesting to explore the idea of embedding AI into these elements to create agent-like MRIE entities which reside purely within the *mixed reality* portion of the MRIE, just as humans reside purely in the physical portion and the robots reside in both.

This paper presents an intelligent environment, called the MR Integrated Environment (MRIE), and a taxonomy which is used to classify techniques within this space. While three interaction techniques have been presented and discussed, these techniques focus on the digital interaction component of the MRIE, and do not cover the physical interaction component. We believe that valuable interaction techniques exist which use both physical and digital interactions simultaneously, and we will explore this in the future.

8. CONCLUSION

Robot technology is advancing steadily, and it is important that we understand the various issues and problems surrounding interaction with robots. The fact that robots reside and interact in both the digital and physical worlds introduces interesting interaction challenges. To meet these challenges, we propose a solution called the MR Integrated Environment (MRIE) which provides a virtual environment of graphics and sound integrated directly into the real world. This environment capitalises on robots being both digital and physical entities, allowing a robot to use the entire shared physical environment as their digital interaction space. Using mixed reality, this environment allows a human user to interact with a robot's ideas and thoughts directly within their shared physical interaction space.

We also offer a taxonomy of the MRIE as a method of organising and classifying the various interaction techniques that this environment offers. As a method of conceptualising our taxonomy we present the notion of an *interaction field*, a four-dimensional space representing the range of potential MRIE interaction techniques. We demonstrate the MRIE and taxonomy through the introduction and discussion of three interaction techniques, *thought crumbs*, *decorations* and *bubblegrams*, and the mapping of these to the taxonomy and the *interaction field*.

In order to evaluate the various MRIE techniques, this paper also presented a design outline of a preliminary prototype. Once this prototype is developed, an evaluation system will be devised and the prototype can be used as a platform for evaluating various MRIE techniques in practice.

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