Ubiquitous Tele-embodiment: Applications and Implications

Eric Paulos paulos@cs.berkeley.edu

John Canny jfc@cs.berkeley.edu

Vive Laboratory
Department of Electrical Engineering and Computer Science
University of California, Berkeley
Berkeley, CA (USA)

Abstract

In the rush into cyberspace we leave our physical presence and our real-world environment behind. The internet, undoubtedly a remarkable modern communications tool, still does not empower us to enter the office of the person at the other end of the connection. We cannot look out their window, admire their furniture, talk to their office mates, tour their laboratory, or walk outside. We lack the equivalent of a body at the other end with which we can move around in, communicate through, and observe with. However, by combining elements of the internet and tele-robotics it is possible to transparently immerse users into navigable real remote worlds filled with rich spatial sensorium and to make such systems accessible from any networked computer in the world, in essence: Tele-embodiment. In this article we describe the evolution and development of one such inexpensive, simple, networked tele-operated mobile robot (tele-mobot) designed to provide this ability. We also discuss several social implications and philosophical questions raised by this research.

1 Introduction

Inexpensive, ubiquitous tele-robots provide a form, a physical avatar, that can be moved around in a remote space. We coined the term *tele-embodiment* to emphasize the importance of the mobile manifestation. Tele-embodiment puts today's physical workplaces, stores, homes, museums, and other real physical spaces online. More importantly, tele-embodiment supports most human activities in those spaces, far beyond what is possible with conventional telecommunication. It preserves the sensory richness, warmth, complexity and unpredictability of the real world. Many intangibles such as atmosphere, morale, chaos, efficiency and communication channels in an organization can only be perceived through unstructured, spontaneous visits to the groups within it. This was the essence of David Packard's strategy of "management by walking around." Most of us still shop by wandering the shelves, looking for specials, seeing the item we want, and asking about its features. Our social interactions are variegated, and we spontaneously move from talking to one individual to another, to a group, to another group, etc. In all these activities, our senses, our mobility, and our situated physical form play essential roles. Ubiquitous tele-embodiment removes the barriers of distance and offers a reasonable facsimile of instantaneous travel to anywhere on earth from any networked computer.

2 Motivation

For decades the telephone has always been within easy reach to provide us with real-time voice communication (Fischer, 1992). But that isn't a substitute for being there. It's still necessary for us to journey from one coast to another for the experience of a conference, trade show, business meeting, or friendly social visit. More recently, the internet has proved itself as a remarkable communication tool, allowing us to exchange text, video, and images, with anyone whose interests we share, professionally or socially.

Several methods of communication have developed within this new medium. Multi-User Dungeons (MUDs), sometimes also called Multi-User Dimensions (Curtis, 1992), and Internet Relay Chat (IRC) lines which are mostly text based systems, already allow us to enter and interact with others across vast distances in shared virtual spaces, often modeled after some real space we inhabit.

In the last few years these virtual spaces, enhanced by the development of internet based interactive virtual reality standards such as VRML (Pesce *et al.*, 1994) and Moving Worlds (Mitra *et al.*, 1996), have become enriched with three-dimensional graphics, texture-mapped furniture, and metaphorical representations of humans or avatars (Stephenson, 1992). Entire vivid and inviting three-dimensional virtual worlds are evolving daily on the internet. By their nature they are fascinatingly playful creations, allowing us to exist in a world free from earthly physical constraints and enter a space where we can fly through the air and pass seamlessly through walls. Just as the development of the WWW has sprouted from the amazing diversity of users operating within it and allowed anyone to publish, so we will find people from all walks of life becoming modern day VR-architects. Many of their creations will indeed be magnificently realistic and interactive. However, we will still lack an interface to the real world in which we live, work, and play.

Furthermore, these virtual systems are only as rich and complex as the models placed within them and often lack the sensory richness, warmth, complexity, chaos, and unpredictability of the real world in which we live. For example, while in real life you may knock over and break a cup, spilling hot coffee onto your friend's lap, current modeling limitations prevent such complex and "scalding" events from transpiring. While this will inevitably change as internet savvy users and emergent behavior empowered autonomous avatars begin to ground-break new spaces with more realistic modeling tools (Mirtich & Canny, 1995) and sophisticated behavior languages (Gosling & McGilton, 1995; Mitra *et al.*, 1996), there will still exist an enormous gap between the richness of the real world in which we live and these virtual modeled worlds.

Video tele-conferencing on the internet provides an arguably more realistic interface into a remote space, but it is more of an enhancement to existing telephone communication technology rather than a new form of communication. With video conferencing we find ourselves fixed, staring almost voyeuristicly through the gaze of an immovable camera atop someone's computer monitor. As actions and people pass across the camera's field of view, we are helpless to pan and track them or follow them into another room. In essence we still lack mobility and autonomy. We cannot control what we see or hear. Even if we had cameras in every room and the ability to switch between them, the experience would still lack the spatial continuity of a walk around a building.

We realized that it was necessary to deliver a more realistic perception of physical embodiment of the user within the remote space being explored. Such as system must immerse the user in the remote world by providing continuity of motion and user control of that motion. These elements would provide the user the visual cues necessary to stitch together the entire visual experiences into a coherent picture of a building and its occupants. We also wanted to provide the user with the means to communicate and interact with the remote world and its real inhabitants using this new system. Furthermore, we wanted such a system to be accessible to any user on the internet with standard software running on currently existing computer architectures.

3 Previous and Related Work

The sensation of embodiment of an individual in a real life distant location has provided more than enough impetus for people to develop remote telepresence systems.

3.1 Historical Telepresence Systems

Methods of achieving telepresence are not new (Sheridan, 1992). Even before the word *robot* (Capek, 1923) had been coined, we find remotely operated mechanical devices, most notably a wireless radio controlled submersible boat by Nikola Tesla in 1898 (Tesla, 1983). It wasn't until decades later when the need to handle dangerous nuclear materials became important did tele-robotics see a re-birth. One of the earliest electrically controlled mechanical teleoperational systems was developed by Goertz (Goertz & Thompson, 1954) in 1954. Many subsequent systems were aimed at safely exploring hostile remote environments such as battlefields, nuclear reactors (Greaves, 1994), deep oceans (Ballard, 1986), mining (Ntuen *et al.*, 1993), and outer space (Weisbin & Lavery, 1994). Additional applications for teleoperated surgery (Green *et al.*, 1995) and manufacturing (Draper, 1995) have been explored by several researchers (Sheridan, 1992; Mosher, 1964; Tomovic, 1969; Moravec, 1988).

Most of these system are quite complex, requiring special purpose dedicated hardware to control and interact with the mechanism in the remote environment. In our system we strived to constrain its development so that it would be accessible to a wide audience without additional, expensive, or extraordinary hardware. In essence, tele-presence for the masses.

3.2 Telepresence on the WWW

The spontaneous growth of the WWW over the past several years has resulted in a plethora of remote controlled mechanical devices which can be accessed via the WWW. Some of these early systems employed fixed cameras in remote spaces where users could observe dynamic behavior such as the consumption and brewing of coffee in a coffee pot or the activity of a favorite pet in its native habitat. One such novel system was the Wearable Wireless Webcam (Mann, 1996) developed by Steve Mann which provided WWW viewers a chance to see the world from the vantage of a camera mounted atop his head. Systems evolved to allow users various levels of control via the WWW such as the LabCam (Wallace, 1996) developed by Richard Wallace. His system allowed remote users to aim a pan/tilt camera using an intuitive imagemap interface.

Progression to intricate control of more degrees of freedom was realized by introducing robots to the WWW. Ken Goldberg *et al.* (Goldberg *et al.*, 1995a) developed a 3 DOF (Degrees Of Freedom) telerobotic system where users were able to explore a remote world with buried objects and, more interestingly, alter it by blowing bursts of compressed air into its sand filled world. Mark Cox (Cox, 1994) developed a system for allowing users to request images from a remotely controlled telescope. Another early remote robotic system, developed by Ken Taylor (Taylor & Trevelyan, 1995), allowed WWW users to remotely manipulate blocks using a robot with an attached gripper. Soon afterwards, we developed Mechanical Gaze (Paulos & Canny, 1996a), a tele-robotic system where uses could control a camera's viewpoint and image resolution to observe various museum artifacts placed within the robot's workspace. Remote visitors created their own dialogue about the various exhibits which were frequently changed. By 1995, Ken Goldberg *et al.* had developed another telerobotic system called the TeleGarden (Goldberg *et al.*, 1995b) in which WWW users are able to observe, plant, and nurture life within a living remote garden. More recently, the first tele-robotic laboratory, Legal Tender (Paulos *et al.*, 1996) came online allowing users to assess the authenticity of a pair of US $100 bills through detailed observation and a set of experiments that physically alter the currency.

Mobile robots capable of browsing larger areas have also been developed by several researchers. Kaplan *et al.* developed a simple system that allowed users to drive a small remote controlled car from a simple network interface while receiving back live video. The results were impressive and raised several issues involving user control under varying network traffic conditions and global accessibility, as this system utilized several applications available on only a limited number of computer architectures. The Learning Robot Lab group at CMU developed Xavier, an WWW mobile robot that could be instructed to travel throughout a floor of a building at CMU and tell jokes. The system performs well in this known environment and is not intended to browse spaces without being given a pre-built model. Although models almost alway aid in navigation, we chose to design a system that would perform reasonably well even without maps, leveraging off of the remote user to aid in the guidance problem. After all, unexpected situations will arise that even a well programmed mobile robot will have difficulty negotiating, while a person will not. As of this writing, well over several hundred interesting mechanical devices are connected to the WWW with more spawning daily.

3.3 Blimp Research

As early at 1881, Albert and Gaston Tissandier constructed a small electric indoor blimp that appeared at an International Exposition on Electricity in Paris (Tissandier, 1884). More recently, there have been several blimp robots built in the last few decades. One outcome of Alan Kay's Vivarium project at the MIT Media Lab in the 1980's resulted in a simple autonomous blimp (Brand, 1987). Mike Caine and Andy Christian (Flynn, 1993) also developed an autonomous blimp which avoided walls during an event sponsored by the MIT AI Lab in 1988. There has also been recent work by the Robot Group in Texas aimed at developing an outdoor autonomous blimp. However, none of these blimps were designed or developed for telepresence. Most of them were large and intended for outdoor or indoor stadium use and ran autonomously. No one, to our knowledge, has proposed using a blimp as a tele-presence device over a network. The originality of our approach is in the combining of lighter-than-air technology for the remote robot with a wide-area network such as the internet for ubiquitous and inexpensive telepresence.

4 Goals

Our primary goal in this work was to provide a truly immersive experience for users tele-visiting a remote space. Furthermore, we constrained our set of solutions by requiring our design to be usable from any networked computer, irregardless of any special hardware. Clearly, this second goal was quite challenging to meet. However, we feel that, barring some extremely extenuating circumstances, any system developed today should be accessible to the entire internet community. Finally, our system must be inexpensive, leveraging wherever possible off of existing hardware. The importance of these goals merits a more detailed description which we elaborate in the following subsections.

4.1 Realism

Drawing from experience in robotics, networking, and interface design, we set out with a goal to design a system that would deliver a truly realistic perception of physical embodiment of the user within a remote space being explored. Such a system must immerse the user in the remote world by providing continuity of motion and user control of that motion. As David Gelernter suggests in his book *Mirror Worlds* (Gelernter, 1992), such systems that gaze into remote spaces should show each visitor exactly what they want to see. This requires the system to provide millions of different views from millions of different focuses on the same object. Certainly visitors will desire to zoom in, pan around, and roam through the world as they choose. More importantly, they should be permitted to explore this space at whatever pace and level of detail they desire. Users should also be free to swivel and rotate their vantage, to get a better look at regions that might be obscured in the initial perspective. All of these elements provide the user the visual cues necessary to stitch together the entire experience into a coherent picture of a building and its occupants. Users should also be provided with the means to communicate and interact with the remote world and its real inhabitants using this system.

4.2 Globally Accessible

The WWW provides an amazingly medium for developing inexpensive, publicly accessible tele-presence tools. Although the WWW can feel extremely restrictive at times, especially when attempting to design an intuitive user interface to a complex robotic system, the benefits of global usability and user familiarity outweigh the drawback of not being able to implement a full tele-presence system. Certainly, we could have chosen to construct custom navigation software for users to download, or even required users to purchase special head-mounts and hardware attachments to interface to their computers. While this would allow us more freedom in the design of the overall system, it would severely restrict the accessibility of the system. Since we consider the quantity and diversity of users on the WWW as one of its most powerful aspects, we chose to constrain the development of our system within the accessibility of WWW users.

4.3 Inexpensive

A final constraint in our design was to develop a system with mostly existing components. We knew that only by designing an inexpensive system could we contemplate the idea of easily and affordably reproducing such systems and using them to populate a variety of spaces and applications. Such widespread use would hopefully result in their adoption into society as a common tool, much as the telephone is today. The ultimate goal: global ubiquitous tele-embodiment.

5 Space Browsers

To meet these goals we developed a device we call a *space browser* (see Figure 1). Essentially, a space browser is a helium-filled blimp of human proportions or smaller with several lightweight motors directly connected to small propellers and no other moving parts. On board the blimp is a color video camera, microphone, speaker, simple electronics, and various radio links. The entire payload is less than 500 grams (typically 250–450 grams). Our design choice was to use the smallest sized blimps that would carry only the necessary cargo, thus making them easily maneuverable down narrow hallways, up stairwells, into elevators, and through doorways. At present we have iterated through countless blimp configurations and have flown blimps ranging in size from 180x90 cm to 120x60 cm. The smaller blimps consume about the same space as a standing person and are thus well suited for moving into groups of people and engaging in conversation with minimal disruption. Even under full power a blimp moves at human walking pace. This provides not only a realistic sensation of walking but also maps well onto the expected delays in the video and motor control signals to and from the blimp though the internet. At present the blimps incorporate no other human-like appearance. In the future, people will want to customize their blimp as they would a virtual avatar. However, with the blimp population still low we feel it is important to maintain a generic external appearance (see section 7 for more discussion on this point).

A user, anywhere on the internet, can use a simple Java (Gosling & McGilton, 1995) applet running within a Java enabled browser to pilot the blimp (see Figure 2). As they guild the blimp up or down, right or left the blimp delivers, via wireless communications, live video and audio to the pilot's machine through standard tele-conferencing software. The pilot observes the real world from the vantage of the blimp while listening to the sounds and conversations within close proximity to the blimp. The user can choose to converse with groups or individuals by simply speaking at their desktop or laptop machine with the sound being delivered via the internet and then a wireless link to the blimp's on-board speaker. The many sensory stimuli delivered by these tools is remarkably similar to those experienced in the real space.

Although we are leveraging off of state of the art video compressions standards, the video bandwidth demands require remote blimp pilots to have access to an ISDN (single B-channel at 56 kbs) or better internet connection. However, recent progress in modem technology promises such bandwidth via standard analogue

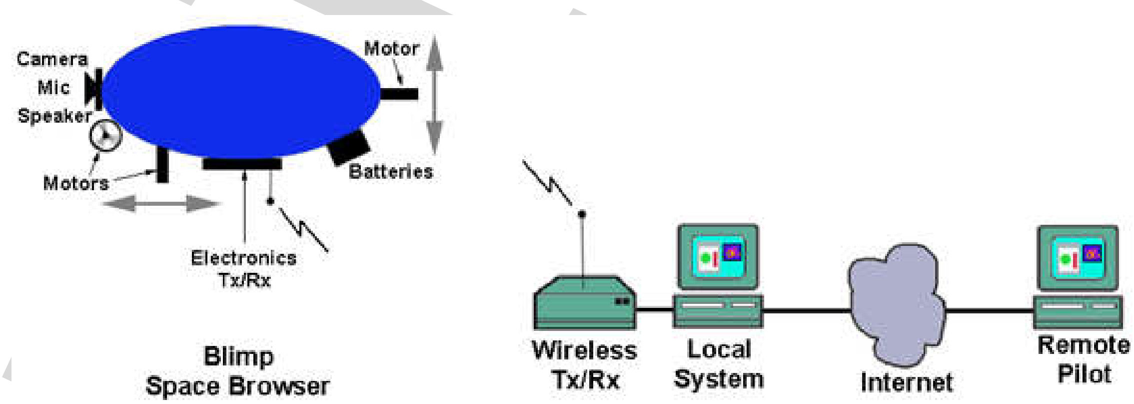

FIGURE 1: Schematic of basic space browser configuration

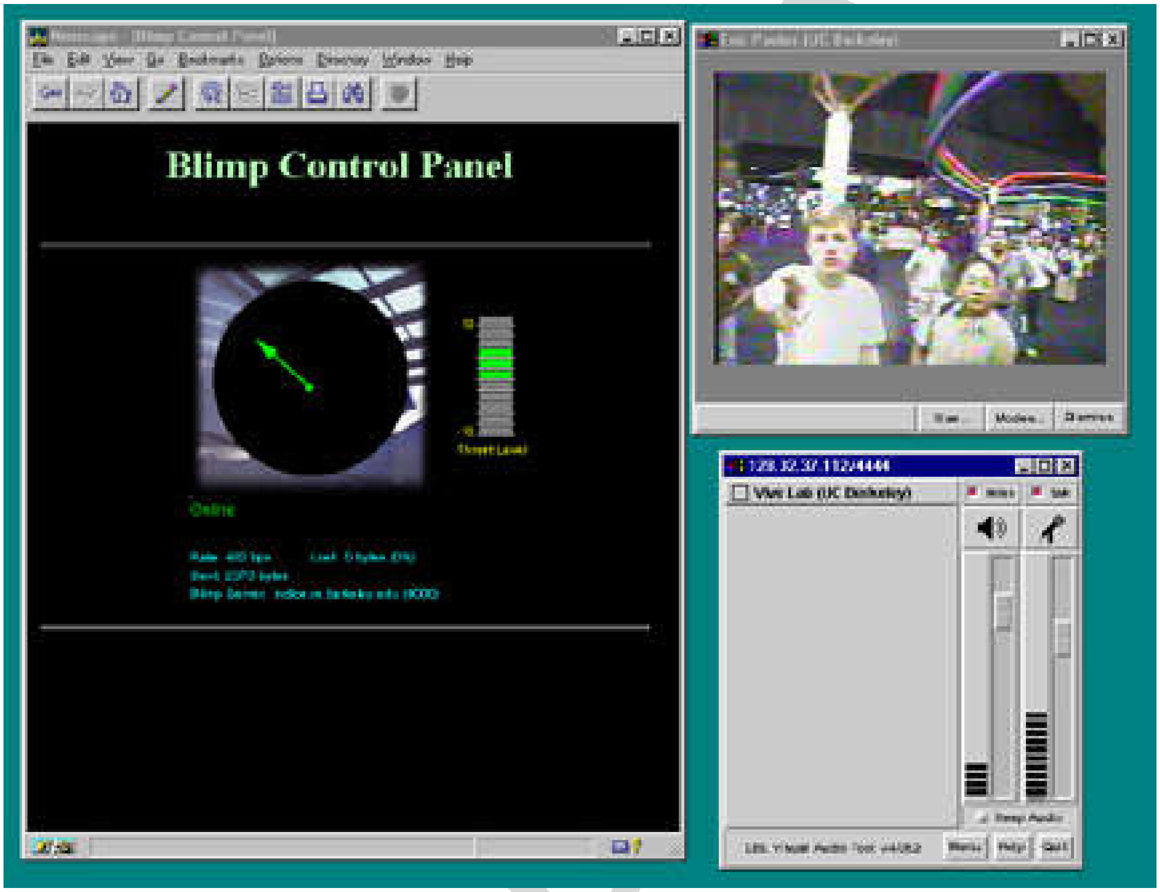

FIGURE 2: The Java user interface to the space browser along with live video and audio feed from blimp as it appears on the remote pilot's computer.

phone lines. Currently, we are using publicly available free tele-conferencing tools initially developed for use on the internet Multicast Backbone (MBone) (Deering, 1991). The video tool, *vic*, developed at Berkeley (McCanne & Jacobson, 1995) implements h.261 video compression and is capable of delivering multicast or unicast network packets. Typical video fram rates of 2–4 fps are adequate for pilots to navigate. Audio is delivered by a similarly developed tool called *vat*. All of these tools are available for most UNIX and PC computers, making space browsers easily accessible to most users.

5.1 Advantages

The blimp offers the possibility of a wide range of spontaneous, group interactions. Telephones and teleconferencing are intrusive media. The recipient must interrupt whatever they are doing to answer the call. The interaction is either one-on-one, or within a pre-arranged group. A space browser cruising by a group can overhear the conversation, recognize the group members, and decide if it is appropriate to enter the conversation.

Our aim is not to replace direct human interaction but rather to extend it. Space browsers allow for mobility in the third-dimension which is a wonderful ability in a building, gallery, or large hall. However, the blimp tele-mobot also offers the user a perception that is richer than human experience since a blimp can travel into places and deliver views from perspectives where no human could travel, such as high above a production facility or conference floor.

A blimp tele-mobot has no problems co-habitating with humans. A collision of a blimp with a fixed obstacle or a person is harmless. Even an out of control blimp poses no real threat to people, while such a statement could not be made for other mobile robots. However, their low weight also means that they cannot be used to transport anything, nor can they open a door, or even push an elevator button.

Difficult robot motion planning problems are avoided by being in the air. While most mobile robots with wheels and tracks struggle with varying floor surfaces, and most cannot handle stairs or even a single step, the blimp tele-mobot simply flies over such problems. The blimp also avoids many of the difficult problems encountered by wheeled and tracked mobile robots when they enter a room littered with books, files, or cables on the floor.

5.2 Disadvantages

Space browsers are far from perfect in that they are currently quite high maintenance. Although there is a motor which provides lift for the blimp, it is not indeded to be used continuously to keep the blimp aloft. Instead the helium level in the blimp must be carefully balanced so as to maintain a near neutral buoyancy in the air. This is sometimes difficult in buildings with drastically varying air temperatures. Worse yet, although it is not susceptible to small air currents created by people walking by it, air conditioning and ventilation ducts have caused more than a few problems with navigation. In at least one instance a blimp was actually sucked onto an air duct and held captive until the air duct could be turned off. It is difficult to solve this problem since it would almost certainly require more powerful motors to combat these unexpected air bursts. However, larger motors translate into larger blimps and at some point the size of the blimp will severely restrict its ability to navigate, rendering it useless to browse spaces within a building.

Stringent weight limitations allow for only a small amount of batteries to be carried on-board, yielding flights of about an hour before batteries need replacement. Although replacement is quick and rather straightforward, this process still prevents the blimp from operating in a round the clock manner, as we would desire. Since the blimp is a robot, we could imagine an automatic system that would cause the blimp to break free from the user and return to some form of docking station to replace its own batteries. However, such systems are extremely difficult to implement and are at the very core of some of the most difficult problems in the field of robotics.

Although novice users have flow the blimp with little or no instruction, it still exhibits erratic behavior. Unlike almost all other robots it is nearly impossible to bring the blimp to a complete halt. We have devised several methods to solve this including one which would literally drop an anchor-like device to the ground. Constructing a more active method to perform this is difficult since accurate location information is not readily available on-board the blimp to aid in such precise positioning. Although the system is simple in design, with the pilot possessing only controls for lift (up/down), turn (left/right), and thrust (forward/back), it often turns into a complex mental challenge to move around. One such problem stems from the fact that a user typically wants to maintain a constant height while flying around, but instead must manually burst the lift motor at regular intervals to maintain that height. To solve this we have incorporated a simple lightweight sonar device onto the blimp to help maintain a constant height. Likewise, various simple aerial acrobatics such as nice ninety-degree turns and flying forward without rotating slightly left or right are difficult. In an attempt to solve this we have incorporated a simple, inexpensive electronic compass weighing less than 25 grams. Both the compass and sonar are carried on board and thus are not susceptible the to network delays experienced by the remote used attempting to correct these problems remotely.

Finally, flying is unfortunately not an innate human ability. To compensate for this we have developed a blimp pilot simulation tool which is interfaced directly through the same Java based navigation window. Rather than controlling an actual blimp, the user flies an accurately modeled blimp in a virtual three-dimensional world in which all collisions and dynamics reflect real world dynamics. This portion of the system is directly based on *Impulse* (Mirtich & Canny, 1995), a tool for accurate dynamic simulation of physically-based systems. Thus, users can inhabit our blimp flight simulator as they await their turn controlling the actual blimp or they can watch the live blimp video as the current pilot navigates.

FIGURE 3: A blimp tele-robotic space browser traversing a building

6 Results

Overall pilots have found the immersive experience of driving a blimp tele-mobot (see Figure 3) to be very compelling. The motion is smooth and natural. We conclude that people are not threatened by the blimp as they typically approach it almost immediately and engage the remote pilot in conversation. Most flights have taken place in Soda Hall, the computer science building on the UC Berkeley campus. However, on several occasions we have taken one or more blimps out of our lab and flown them where people can interact with them away from a laboratory environment. We did this not only to gauge the level of acceptance and usability of blimps by humans but also to test out the flexibility of our design in terms of ease of transport, setup, and operation in a remote space. The later being extremely important if we have hopes of such devices becoming ubiquitous home consumer items.

Although it may not be apparent, there is little limitation to the number of blimps that can operate in the same space at the same time. In fact we have flow more than one blimp on several occasions both in our lab and at remote locations. Several flights have been made at the Exploratorium, a hands on technology museum in San Francisco, providing the blimp and its remote pilot the opportunity to interact with a wide range of people, including small children. In fact during this test several children accidently placed their fingers directly into protective housing for the propeller. Although the propeller struck their fingers with full force, none of the children were injured, reinforcing our claim that space browsers can safely co-habitate with humans. Several blimps also made the trip to the Digital Bayou at SIGGRAPH (Paulos & Canny, 1996b) in New Orleans where they provided a remote proxy for people at the conference and for those that could not attend. Other locations include navigating through and surviving a hostile environment where heavy industrial machinery was in operation, the UC Berkeley Paleontology Museum including browsing a Tyrannosaurus Rex skeleton several stories high, and cross country flights where individuals in New York successfully piloted blimps in California. In several of these locations additional publicly available networking tools such as the Video Gateway (Amir *et al.*, 1995) were employed to tunnel internet traffic from local networks to more desirable portions of the internet which were capable of routing multicast packets. This allowed anyone connected to any portion of the Mbone to view and listen to the blimp's video and audio feed.

7 Social and Cultural Implications

Space browsers provide a new method of remote human interaction. By empowering users to easily travel vast distances away from their desktop or laptop and interact in a familiar manner with other individuals, we have bridged many gaps in our society. With the telephone users around the world can speak to each other.

With the extension of MUDs and teleconferencing tools, communication lines have widened. However, with space browsers, users can experience the visual and audio sensation of a remote space as well as guide their viewpoint. They can meet others and take walks and tours with them. They can fly the blimp and guide groups (or be guided) though buildings, laboratories, museums, etc. It is quite possible that real friendships and relationships can develop in a near seamless manner across these distance spaces. Many of today's long trips can be replaced by employing a space browser. They will also provide a new inexpensive method of travel for those currently under monetary or time constraints. In fact they can bring expertise into offices and homes. Imagine a rare, yet remote, archaeological discovery where in a matter of hours, every expert in the world could travel to the actual site, gather the data that they need, view any detail they desired in the entire area, and leave comments for other scientists. In another scenario a simple tele-mobot allows a woman to receive a home medical exam from a medical expert in Europe. Shopping for a new home? Perhaps a ten minute flight through a house, whenever you want, will save you and a realtor time tracking down the perfect home. Clearly, the possible applications for such tools are enormous. Nevertheless, there are numerous issues, which we discuss in this section, that will inevitably become important (if they have not already) in this research area.

7.1 Human Acceptance and Interaction

Although we have observed people interacting in an extremely natural way with the blimp space browsers, there are several issues that make it disconcerting. Clearly there is an asymmetry in a blimp–human encounter. The space browser does not manifest body language or facial gestures which may cause unease or defensiveness in one or both parties. One of the most problematic elements of this issue is that, although the blimp pilot can observe the remote participants, those participants cannot see the pilot. In section 8 we address several solutions to this problem. However, there are interesting social issues that arise from this problem.

A closely related psychological experiment undertaken in the 1970's by Stanley Milgram (Milgram, 1977) involved the use of what he called *Cyranoids*, so named for their relation to the character Cyrano de Bergerac in Edmond Rostand's play by the same name (Rostand, 1923). Cyranoids are people who do not speak thoughts originating in their own central nervous system. Rather, the words that they speak to a listener originate in the mind of another person, called the source, who can listen to the space around the cyranoid and transmits words to the cyranoid by means of a wireless transmitter. A tiny radio receiver inconspicuously fitted into the cyranoid's ear is used to receive the words from the source individual. The similarity is apparent in that space browsers act as cyranoids for the pilot of the blimp, or what Milgram would call the source. By carefully constructing experiments where individuals would interact with a cyranoid with characteristics differing significantly from those of the source, Milgram was able to gauge the very essence of human dependence upon the correspondence of a person's visual appearance and their persona.

For space browsers, we are interested in the capability of people to interact with blimp-shaped avatars (i.e. cyranoids) in a natural way. Milgram concluded from his experiments that people are unable to separate the cyranoid from the source and always assume that the individual with which they are interacting is the cyranoid. Remember, that this is with near perfect information since the individual can ask any question and observe every detail of the cyranoid's actions. The main result we can draw from Milgram's work is that appearance is extremely important in human interaction. Appearance is so important that people continue to believe that the person with which they are interacting is the person in front of them even when every element except the vocal-movement is removed from that person to another distant person. This makes blimps ideal as remote interaction proxies, since people will fail to associate any human persona directly onto the blimp and instead almost always correctly identify the remote source as the person with which they are interacting, the blimp's pilot. There have been a few times where people did believe that the blimp was acting in some sort of autonomous mode, but in almost all of these cases there was no audio interaction and hence very little information was available upon which to discover the actual source. While people often suggest placing eyes on the blimp or forming it with arms and legs, it is clear that by remaining non-anthropomorphic blimps will perform better as communication tools. A blimp will always take on the appropriate persona of the person flying it since people will not observe the blimp and form immediate expectations about the sex, race, age, etc. of the individual flying the blimp. The blimp will, in a sense, inherit any of those elements directly from the correct source, the pilot, and not from the blimp's appearance. However, we do agree that the addition of some purely aestetic blimp features will provide important visual queues for people interacting locally with it. That is, these features will convey to people around the blimp information such as the fact that there is a camera on the blimp, the location of the camera, the fact that there is a two way audio link, and where the speaker and microphone are located.

7.2 Authenticity

While developers of tele-robotic tools on the internet strive to create the most realistic impression of "presence" in the remote space, users are all too often left wondering if what is on the other end is real. After all they have little information to go on. In fact, since all of the information delivered to them is digital as a result of the underlying transport mechanism, any images and video could easily be faked by cleverly fetching them from a catalogue of pre-scanned images. In fact there have been a number of creators of purportedly tele-robotic sites in the last year that have been exposed as charlatans.

We find that in a typical tele-robotic system, users often perform a series of what appear to be *ad hoc* tests in an attempt to convince themselves that the tele-robotic system is in fact authentic. Several users of our system have in fact claimed that implementing a real system would be much to difficult and that what we have presented is merely a hoax. Our belief is that users are developing their own form of what we call the *Tele-robotic Turing Test*, named to reflect its obvious relation to a test described by Alan Turing in 1950 (Turing, 1950). In the original Turing Test, an experimenter is connected to a human and a machine via a simple terminal. Through dialogue conducted only through the terminal, the user must determine which of the two candidates is the machine and which is the human. If after a reasonable amount of time, the interrogator cannot make a decision the machine is labeled intelligent. Similarly, tele-robotic experimenters must go through a limiting set of possible remote queries of the remote robot. However, unlike the actual Turing Test, the choice is not between a machine and a person. Instead, the user is weighing what they believe can be digitally faked using existing technology and their knowledge of the real world from their daily life.

We developed one such site to directly address this issue of authenticity in relation to WWW based tele-robotics. This tele-robotic laboratory, called Legal Tender (Paulos *et al.*, 1996), allows remote users to closely examine a pair of US $100 bills. Remote analysts are asked to assess the authenticity of the bills. Analysts may, if they choose, perform an experiment such as a puncture, thermal, or abrasion test to aid them in their decision.

Perhaps at the core of this debate is the philosophical issue of epistemology, which is a branch of philosophy concerning the nature, origin, scope, and limits of human knowledge. When users engage and question such remote systems we claim that they are in fact exhibiting a new form of this philosophical question, which we call *tele-epistemology*, originally coined by Ken Goldberg (Goldberg & Spaid, 1996).

7.3 Privacy

For many, airborne blimps inhabiting a building are nothing more than platforms to launch reconnaissance attacks on other individuals. However, although the blimps are designed to be small and agile so that they can navigate within a building, they have no super human abilities that enable them to pass through walls, push elevator buttons, unlock doors, or for that matter even open a closed door. In fact, they cannot travel into most places already prohibited by humans. Certainly, they can fly over barriers and partitions, but so too can humans scale such obstructions. Also, although they are designed to be unobtrusive, they are far from imperceptibly. Since they are highly visible, they cannot provide the means to support a hidden camera. Finally, blimps are not silent, their propellers create a notable fan-like whirl that is perceptible from even around a corner, warning one of an approaching blimp. Beside carrying the power, electronics, and radio equipment, the blimp also stands in as a physical avatar for the remote user and hence the design of a stealth blimp would be counter productive to its use as a communication tool. While every effort as been made in its design to be a benevolent tool, we cannot rightfully make claims that such a system will never be used maliciously.

7.4 Responsibility

So far most of the WWW based tele-robotic systems have been intentionally designed to be safe. Although many of these systems have been developed on standard industrial robots where safety is an issue, they are typically kept behind locked doors, preventing an unsuspecting person from accidentally placing some part of their body in harm's way of the robot. Even our blimps, which actually co-habitate with people in their natural setting, are intentionally designed to be safe.

However, fundamentally there is nothing preventing people from intentionally or accidentally creating systems where physical structural damage or human injury is possible. In fact such system already exists in several tele-robotic installations. The difference is that none of these systems has been made accessible to the entire WWW community. However, it is quite likely that such systems will be brought to the WWW. When they do there will be immediate issues of responsibility in terms of property damage and human injury. Does the responsibility rest in the hands of the creator of such a system or in the remote individual controlling the system? In the case of the latter it is entirely possible, due to the easy of anonymity on the internet, that the identity of the remote user may never be know. We are all aware of the interest in hacking into computers and manipulating, stealing, or destroying digital data. One can easily image the fascination of taking control of a potentially dangerous device, to use to one's only ends. There are more questions than answers in this area, only that extreme precautions should be taken when developing such systems. Nevertheless, we will inevitably cross paths with this issue in the years ahead as WWW based tele-robotics evolves.

8 Current and Future Research

Undoubtedly, countless remotely controlled physically devices will come online in the next few years. Many of them will provide the sensation of tele-embodiment. Technology often moves at a blinding pace and future predictions are difficult to make. However, we see at present a few new immediate areas our research into tele-embodiment will take.

8.1 Blimps

Although our current blimps have performed well under a variety of conditions, there are numerous improvement that could be made. Many of the improvements ideas that come to mind can immediately be eliminated due to weight restrictions. For example, one may wish to add some form of Global Positioning System (GPS) on-board. While this may be possible in the future, current GPS systems weigh on the order of 250 grams. More immediate design plans include the incorporation of a simple sonar for height control and a small electronic compass for elementary positioning and to aid in basic maneuvering.

Longer term goals are better interactivity, video display of the pilot on-board the blimp, a movable laser pointer that users can use to point at objects, and an eyeball motor for quickly changing the viewpoint of the camera without moving the entire blimp. We have also discussed various ideas that would allow blimps to transport small items, automatically recharge their battery packs, and travel outdoors. The high motion style video generated by the on-board blimp camera calls for the adoption of new video compressions standards such as h.263 which benefit from the incorporation of motion vectors and half pixel interpolation. At some point we imagine much higher levels of control where users can place the blimp into a follow mode which will cause it to follow the person or object within the video image. Likewise, we hope to develop a system that allows a person to select a feature in the video image which the blimp will then approach. We would also like to incorporate it as a useful tool into existing research for creating realistic synthetic views of existing architectural scenes by using the blimp as a platform for generating a sparse set of still photographs (Debevec *et al.*, 1996). Fundamentally, our research draws as much on the sociology of group interactions as on sensing and actuation techniques, and we need the former to drive our choices for the latter.

8.2 Carts

Another approach we are exploring is to develop other systems to provide tele-embodiment. One such system is a terrestrial based four wheeled cart with on-board audio and video systems similar to those on the blimp. However, unlike the blimp, the cart will be able to travel outdoors, be much lower maintenance, and provide much longer battery life since its weight restriction is greatly relaxed. The cart must still adhere to the same goals we set forth for the blimp (see section 4), especially in terms of safety when interacting with other humans. In addition we are insisting that these carts be capable of negotiating stairs safely. Furthermore, the cart will leverage off of existing wireless communication infrastructures being developed in parallel for mobile computing. We expect that when our cart systems are fully operational, many such wireless networks will already be in place, making the accessible world of carts much larger than that of blimps.

There is no one simple solution to tele-embodiment. The blimps are difficult to control and impose severe weight restrictions while the carts fail to provide the allure of super-human mobility and complete freedom in the third dimension. We feel that this not a problem. In fact we believe that there will always be many varied, inexpensive, accessible tele-embodiment tools, each with their own set of applications.

9 Conclusion

We believe that the technologies needed to support ubiquitous tele-embodiment are all in place now, and they are surprisingly inexpensive. Our entire space browser prototype cost under two-thousand US dollars. In quantity it should be possible to place such systems within the range of the typical home consumer. Compared to an true visit, the space browser lacks very little. We do not have enough experience yet to say whether something essential is lost and if so how to compensate for it. Nevertheless, it is clear that these systems represent a new tele-communication form. Our position is that while the telephone and video teleconferencing lack some essential elements of presence in the remote space, space browsers do not. With their low cost and enormous commercial potential, it is quite possible that such devices will become ubiquitous home computer accessories. Widespread use of mobot proxies will result in many mobot-mobot encounters. In that case, it may make more sense to meet in a real space remote to all individuals. Imagine a lunch break where you meet several friends from around the world to fly together, each with separate space browsers, through the latest exhibits in the Louvre. Realistically, it will be a long time before the majority of people feel comfortable passing seamlessly between their immediate real world and the reality of tele-embodied worlds. In the mean time, space browsers and other forms of tele-mobots will provide a way for an individual, no matter how far away, to participate in a rich and natural way, within another environment.

Acknowledgments

Funding for this research was provided by National Science Foundation Grant #FD93-19412 and Darpa AO #B454. We would also like to thank the following individuals for numerous enlightening personal discussions surrounding this work: Ken Goldberg, Benjamin Zorn, Mark Pauline, Michael Fogarty, Greg Leyh, Warren Flynn, Anita Flynn, Paul Debevec, Richard Wallace, and David Pescovitz.

References

Amir, E., McCanne, S., & Zhang, H. (1995). An application level video gateway. In *ACM Multimedia.*

Ballard, R. D. (1986). A last long look at the titanic. *National Geographic.*

Brand, S. (1987). *The Media Lab: Inventing the future at MIT.* Penguin.

Capek, K. (1923). *R.U.R (Rossum's Universal Robots).* Doubleday, Page, and Company.

Cox, M. (1994). Robotic telesopes: An interactive exhibit on the world-wide web. In *Second International World Wide Web Conference*.

Curtis, P. (1992). Mudding: Social phenomena in text-based virtual realities. In *Directions and Implications of Advanced Computing (DIAC) Symposium*.

Debevec, P., Taylor, C., & Malik, J. (1996). Modeling and rendering architecture from photographs. *SIGGRAPH*.

Deering, S. E. (1991). *Multicast Routing in a Datagram Internetwork*. PhD thesis, Stanford University.

Draper, J. (1995). Teleoperators for advanced manufacturing: applications and human factors callenges. In *International Journal of Human Factors in Manufacturing*.

Fischer, C. S. (1992). *America Calling: A Social History of the Telephone to 1940*. University of California Press.

Flynn, A. (1993). *Mobile Robots: Inspiration to Implementation*. AK Peters.

Gelernter, D. (1992). *Mirror Worlds*. Oxford University Press.

Goertz, R. & Thompson, R. (1954). Electronically controlled manipulator. *Nucleonics*.

Goldberg, K., Mascha, M., Gentner, S., Rothenberg, N., Sutter, C., & Wiegley, J. (1995a). Robot teleoperation via www. In *International Conference on Robotics and Automation*. IEEE.

Goldberg, K., Santarromana, J., Bekey, G., Gentner, S., Morris, R., Sutter, C., Wiegley, J., & Berger, E. (1995b). The telegarden. In *SIGGRAPH*.

Goldberg, K. & Spaid, S. (1996). Telepistemology. *Wired*, page 232.

Gosling, J. & McGilton, H. (1995). The java language environment: A white paper. Technical report, Sun Microsystem.

Greaves, A. (1994). State of the art in nuclear telerobotic: focus on the man/machine connection. In *Transations of the American Nuclear Society*.

Green, P., Hill, J., Jensen, J., & Shah, A. (1995). Telepresence surgery. In *IEEE Engineering in Medicine and Biology Magazine*.

Mann, S. (1996). 'smart clothing': Wearable multimedia and 'personal imaging' to restore the balance between people and their intelligent environments. In *Proceedings, ACM Multimedia 96*.

McCanne, S. & Jacobson, V. (1995). Vic: A flexible framework for packet video. In *ACM Multimedia*, pages 511–522.

Milgram, S. (1977). *The Individual in a Socal World: Essays and Experiments*. McGraw-Hill, Inc.

Mirtich, B. & Canny, J. (1995). Impulse-based simulation of rigid bodies. In *Symposium on Interactive 3D Graphics*, New York. ACM Press.

Mitra, Honda, Y., Matsuda, K., Bell, G., Yu, C., & Marrin, C. (1996). Moving worlds: behaviors for VRML. In *SGI Technical Report*.

Moravec, H. (1988). *Mind Children. The Future of Robot and Human Intellegence*. Harvard University Press.

Mosher, R. S. (1964). Industrial manipulators. *Scientific American*, 211(4).

Ntuen, C., Park, E., & Kimm, S. (1993). A blackboard architecture for human-machine interface in mining teleoperation. In *Human Computer Interaction*.

Paulos, E. & Canny, J. (1995). A world wide web telerobotic remote environment browser. In *Fourth International World Wide Web Conference*.

Paulos, E. & Canny, J. (1996a). Delivering real reality to the world wide web via telerobotics. In *IEEE International Conference on Robotics and Automation*.

Paulos, E. & Canny, J. (1996b). Space browsers: A tool for ubiquitous tele-embodiment. In *SIGGRAPH Digital Bayou Visual Proceedings*, page 83.

Paulos, E., Pauline, M., Canny, J., & Donith, J. (1996). Legal tender. In *SIGGRAPH Bridge Art Show Visual Proceedings*, pages 43–44.

Pesce, M., Kennard, P., & Parisi, A. (1994). Cyberspace. In *First International WWW Conference*.

Rostand, E. (1923). *Cyrano de Bergerac*. The Modern Library.

Sheridan, T. B. (1992). *Telerobotics, Automation and Human Supervisory Control*. MIT Press.

Stephenson, N. (1992). *Snow Crash*. Bantam Books.

Taylor, K. & Trevelyan, J. (1995). Australia's telerobot on the web. In *International Symposium On Industrial Robots*.

Tesla, N. (1983). *My Inventions: The Autobiography of Nikola Tesla*. Hart Brothers.

Tissandier, G. (1884). *Application de L'Electricite: A La Navigation Aerienne*. Imprimerie Jules Tremblay.

Tomovic, R. (1969). On man-machine control. *Automatica*, 5.

Turing, A. (1950). Computing machinery and intelligence. *Mind*, 59(236):433–460.

Wallace, R. (1996). A notebook active vision system. *IU Workshop*.

Weisbin, C. & Lavery, D. (1994). NASA rover and telerobotics technology program. In *IEEE Conference on Robotics and Automation Magazine*.