MIXED REALITY ENTERTAINMENT
WITH WEARABLE COMPUTERS

FONG SIEW WAN

(Master in Engineering, National University of Singapore)

A THESIS SUBMITTED
FOR THE DEGREE OF MASTER OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
NATIONAL UNIVERSITY OF SINGAPORE
2003

Acknowledgement

I would like to express my gratitude to all those who gave me the possibility to complete this thesis. First and foremost, I want to thank the Defence Science and Technology Authority (DSTA) of Singapore for the financial support in this research project. Especially to the officers in-charged, Ms Lilian Ng and Mr Choo Hui Wei, I thank you for all your suggestions and encouragement throughout the project.

I am deeply indebted to my supervisor Dr. Adrian Cheok whose help, stimulating suggestions and encouragement helped me in all the time of research for and writing of this thesis.

My former colleagues from the Digital Systems and Applications lab, Power lab, and Human Interface Technology lab supported me in numerous aspects of my work. I want to thank them for all their help, support, interest and valuable hints. Especially I am obliged to Dr Chen XiangDong, Ms Liu Wei, Dr Simon Prince, Dr Farzam Farbiz, and Mr Goh Kok Hwee. I also want to thank Mr Lee Meng Huang for all his assistance during the initial phase of the project and demonstration.

Especially, I would like to give my special thanks to my family whose patient love enabled me to complete this work.

Contents

Abstract

Computing technology is rapidly advancing for the past few decades; providing us with ever greater computing power, storage capacity, and portability. With the recent proliferation of portable computing devices such as laptop, palmtop, and tablet PC, I am envisioning a future of mobile computing becoming the mainstream technology thereby reducing the desktop to a historical relic. Mobile computing is realized with the employment of a wearable computer. In this thesis, I will describe the design and development of the wearable computer named 'DSTAR'. This powerful wearable computer is complete with a head mounted display (HMD) with camera attached, a main system of small form factor (PC 104 form factor), and a novel input device (Twiddler2). In addition to that, I have also added a Wireless LAN card, an inertial sensory system (InertiaCube2), a Bluetooth device, and a Global Positioning System (GPS) receiver (or a Dead Reackoning Module, DRM, in the later system) to enable the wearable computer to support the implementation of augmented reality and networking software applications.

Three wearable computing applications are developed: 'Game City', 'Interactive Theater', and 'Human Pacman'. These systems support multi-players in a wide outdoor area with total mobility in an attempt to renew traditional physicalness in gameplay in computer entertainment. Tracking and navigation modules are incorporated by overlaying the video stream captured by the head-mounted camera with 2D text or 3D virtual objects. At the same time, wireless LAN is set up to support communication between players so as to explore the various aspect of social gaming. Tangible interaction between physical object and its virtual counterpart is incorporated into the gameplay to provide the player with a new experience of direct physical interaction with his computer. Also, they can experience seamless transitions between the virtual and the real world in the systems.

In the last part of the thesis, various mobile computing problems encountered in the areas of wireless communication, mobility, and portability are described in details. I will also take a look of the theme of ubiquitous computing embedded in our applications. I studied several issues such as tangible interface and context awareness in outdoor environment in the domain of ‘Human Pacman’. Lastly, I present the reader with human computer interaction (HCI) design concerns of the system. Design decisions are justified in adherence to the wisdom from HCI studies.

List of Figures

Chapter 1

Introduction

Early in the Age of Science, the notion of personal computing was an obscure heresy in the ranks of computing scientists. A mere thirty years ago, the overwhelming majority of the people who designed, manufactured, programmed, and used computers subscribed to a single idea about the proper place of computers in society: “Computers are mysterious devices meant to be used in mathematical calculations”. Computer technology was believed to be too fragile, valuable, and complicated for nonspecialists. Fortunately, there was an emerging group of dissenters, who opposed to the conventional thinking about how a computer might be used. They shared a vision of personal computing in which computers would be used to enhance the creative aspects of human intelligence for everyone (not just the technocognoscenti).

Ever since then, computer has moved beyond the realm of mathematical calculation into communication, entertainment, education, and other fields in the multitudinous facets of modern livelihood. For the past fifteen years or so, scientists, engineers and futurists have been thinking about how computers might be used to assist the operation of human minds in nonmathematical ways. Indeed as it stands today, personal computing technology has made the computer into a device which is approximating the theoretical discovery of a “Universal Machine”, which is not actually a tangible device but a mathematical description of a machine capable of simulating the actions of any other machine. In other words, once you have created a general-purpose machine that can imitate any other machine, the future development of the tool depends only on what tasks you can think to do with it. For example, the personal computer is now very commonly used to watch television programs (emulating a television set), to play games (emulating a game console), and many other forms of work and play.

Because of the many uses of the personal computer, it has gained a strong foothold in the society of today as an indispensable commodity in every household and workplace. However, the high proliferation of computers is achieved, at least to a large proportion of the human inhabitants of the world, at the expense of psychological ease and tranquility of handling day-to-day life. “Computer literacy” and other obfuscating technical jargon remain confusing to the masses. This should not be happening because the reason for building a personal computer in the first place was to enable people to do what people do best by using machines to do what machines do best. Many people are afraid of today’s computers because they have been told that these machines are smarter than they are - a deception that is reinforced by the rituals that novices have been forced to undergo in order to use computers. In fact, the burden of communication should be on the machine. A computer that is difficult to use is a computer that is too dumb to understand what we want. Therefore the next step in personal computing development is rightly the evolvement of a computing environment that takes the intelligence of its own, i.e. a kind of computer human interface that bridges the communication barrier between the two parties for better understanding and cooperation.

1.1 Objectives

This thesis examines the new paradigm in personal computing with development of a "wearable computer" (this term will be defined and explained in chapter two) for unforeseen level of mobility, sociality, and physical interactivity in computing. With the wearable computer that is capable of providing 'always on' and 'always available' computing power, I explore the various advantages of users' embracing machine empowerment as they physically move about (mobile computing). When people are donning their wearable computers, they are interconnected via wireless communication network. I have incorporated the study of social interactions between the users in terms of how physical proximity affects inter-personal communication in the virtual realm (over Wireless LAN 802.11b and Bluetooth network). Physical interactivity is experimented by implementing the concept of tangible computing in which physical objects are linked to their virtual counterparts using sensing technology such that when the user is handling the physical objects, certain corresponding effects are registered in the computer.

I am also addressing several challenges of wearable computers, for instance how to minimize their weight and bulkiness, how and where to locate the display, and what kind of data entry device to provide. With all the groundwork described built up, I arrive at the ultimate aim of the thesis, which is to explore wearable computing applications that are capable of improving the quality of life.

1.2 Scope

Our primary concern is on wearable computer applications and the human computer interaction aspects. I have purchased off-the-shelf single board computers;

their accessories such as graphic cards, network card etc.; and input/output devices. However, all the assembling work, including the design and fabrication of PCB boards for power supply using video camcorder batteries, is done in lab. This arrangement provides the opportunity to ponder the challenges of wearable computers as mentioned in the previous section.

Augmented reality (AR) technology (defined in the next chapter) is widely applied in wearable computing applications. However detail mathematical calculation of localization is derived by previous works on sensor and visual tracking. I concentrate on building AR software that allows me to update sensors' data in real-time and to overlay virtual 3D objects in the video stream captured by the head mounted camera.

Registration of virtual objects in the real world is done using inertial sensor and Global Positioning System. The interface program for the sensors is custom-built with providence for expendability and upgradability using object oriented programming methodology. This is done in an effort to ensure ease of future software development.

It must be noted that the live-capturing of actors in Interactive Theater (refer to chapter 4) is done using the results from Simon Prince's work on 3DLive [1]. However, all other components of the application software, such as the game engine, the networking modules, and the Bluetooth communication codes, are written by me with assistance from researcher engineers in the lab as mentioned in the 'Acknowledgement' chapter. Nevertheless, the applications presented in this thesis are prototypes for the purpose of demonstrating the potential and studying the various aspects of mobile computing using wearable computers. More refinement and customized hardware development are required before these applications can be commercialized.

1.3 Research Contributions

The research reported in this thesis is done systematically over the period of two years. The sequence of events are detailed in the following list:

- *Surveying Wearable Computer Components*: The technology used in building the wearable computer consisted of three major components: the system unit, a viewing headset and an input device. At the initial stage of the project, I did a thorough survey about all components required in the building up of the wearable computer. This was to ensure I have purchased the most suitable and up-to-date devices in this field of rapid advancement.

- *Designing Wearable Computer*: I proceeded to plan for the physical arrangement of the components of wearable computers. Designs were drawn up for the prototypes.

- *Sensors Testing and Interface Software Development*: Upon receiving the Global Positioning System (GPS) receiver, the inertial sensor, and the digital compass, I went on to do location testing and proceeded to develop software that supported the communication between the wearable computer and the sensors.

- *Assembling Wearable Computer with Designing and Fabricating PCB Board for Power Supply*: The wearable computer components were delivered about three months after the purchase order was sent. I assembled the components according to my initial design and made modification where deem necessary. The power for the wearable computer was derived from two camcorder batteries. However because of the stringent power requirement of various components, i have to built my own regulator board to connect the batteries to the wearable computer.

- *Developing Tracking and Navigation Software*: When the wearable computer was fully functional, I went on to integrate it with the sensors. Using the sensor interface software previously developed, I progressed to develop tracking and navigation software.

- *Developing 2D Text Overlay for Indoor Tracking*: I ventured into augmented reality application development by writing the software required to overlay 2D text labels on real objects.

- *Developing 2D Text Overlay for Outdoor Tracking and Navigation*: Overlay software was integrated with the tracking and navigation software in an attempt to develop an outdoor tracking and navigation application.

- *Developing 'Game City'*: First complete wearable computing application with simple game engine, and network communication. This work is documented as a poster paper titled, "Game-City: A Ubiquitous Large Area Multi-Interface Mixed Reality Game Space for Wearable Computers"[2].

- *Developing 'Interactive Theater'*: 3DLive technology was used to capture live 3D actors in this application which was developed to bring forth a new interactive theater experience that encompassed the exciting virtual reality environment navigation as in Touch-Space. This work is published as a conference paper[3].

- *Developing Bluetooth Communication Software*: I have acquired the Bluetooth software development toolkit for the development of customized software on Bluetooth communication.

- *Developing Multi-player Network Communication Software*: With the Wireless LAN network as the backbone, I have written the software to support communication between several wearable computers.
- *Building Touch Sensor for Tangible Interaction Application*: I investigated the use of 'tangible interaction' with the use of touch sensors that were built in lab. The touch sensor was connected to a tiny computer (the 'Matchbox' computer, refer to chapter three). Communication between the tiny computer and the wearable computer was done via Bluetooth devices attached to each of them.
- *Developing 'Human Pacman'*: The most ambitious application in this thesis was the 'Human Pacman' (for details, refer to chapter five). It is physical computer fantasy game integrated with human-social and mobile-gaming that stresses on collaboration and competition between players with emphasis on physicality, mobility, social interaction, and ubiquitous computing. The 'Human Pacman' is presented in two conferences NETGAMES 2003 [4] and Mobile HCI 2003 [5]. It has also been invited to be documented as a journal paper [6]. A demonstration of the 'Human Pacman' is presented in the premier international conference for human-computer interaction, CHI'04 [7].

At the end of the projects, I summarize the main contributions of this thesis as the following:

1. Background on wearable computer and augmented reality is discussed. Commercial and research wearable systems are included to present the user with the flavor of current wearable computer technology. Components of wearable computer and various software applications are studied. All these lead to the

development of the wearable computer 'DSTAR' (refer to section "DSTAR Wearable Computer" in chapter three) which is used for all software applications described in this thesis.

2. Construction of 'DSTAR' wearable computer is presented in detail. Some prior experiences are shared too as reference for future projects. Technical difficulties and limitations are discussed.
3. Wearable computing applications called 'Game City', 'Interactive Theater', and 'Human Pacman' are described in details. These novel computer entertainment systems are designed to explore various aspects of mobile computing. Valuable insights and experiences are gained through experimenting physically with the sensors and wearable computers.
4. Technical aspects of mobile computing and HCI are discussed in depth in the context of 'Human Pacman'. Design considerations, problems faced, as well as limitations of current technology are presented.

1.4 Organization

This thesis is organized into seven chapters, the contents of which are as follows:

Chapter two provides an overview of wearable computer: its historical context and fundamental issues. Special attention is paid to research and commercial systems previously developed. After that, components of wearable computers available on the market is surveyed. The chapter is rounded up with discussion on common software applications based on wearable computer.

Chapter three introduces the development of the wearable computer. Details of the development phases are given, along with the final hardware and software designs. Problems and limitations encountered are given to serve as guidelines for future systems.

Chapter four describes the development of two wearable computing applications: 'Game City' and 'Interactive Theater'. Background on interactive theater is given to provide the artistic context upon which this work is based on. Chapter five describes the building up of 'Human Pacman'. Details about the gameplay are described.

Chapter six considers the software design and Human Computer Interaction (HCI) issues in 'Human Pacman'. Main topics discussed include mobile services, ubiquitous computing issues, and HCI design concerns. After that various challenges hindering wearable computing applications from gaining mass acceptance are suggested. Chapter seven provides a summary of the thesis with a discussion of future development and impact of this work.

Chapter 2

Background: Wearable Computer & Augmented Reality

What is a wearable computer? According to Steve Mann [8][1], a wearable computer is a computer that is subsumed into the personal space of the user, controlled by the user, and has both operational and interactional constancy, i.e. is always on and always accessible. Although the idea of wearable computer is consistent with the current trend of computing being away from the desktop paradigm and towards smaller mobile tools, why do we need a new genre of computing equipments when our world is already infested by popular personal mobile devices such as laptop, pda (personal digital assistant), and handphone?

Laptop is mobile only to the extend that the user can carry it with him; he can hardly use it while walking or driving a car without posing serious life threats to other pedestrians or car drivers. Smaller devices, such as palmtop and pda, still suffer from poor usability - awkward input device, bad user interface, and low computing, storage and battery power. Moreover, the user has to consistently

---

[1] Steve Mann is considered by many to be the pioneer of wearable computers. He termed those computer systems ‘WearComp’.

perform data synchronization with the desktop where the main database is stored for up-to-date information. The last type of mobile devices, such as handphone and pager, are only good for specific tasks; there is hardly any support for interoperability and programmability. Therefore, wearable computer attempts to solve these problems, to provide "always on", instant access to information and services, and to provide a more intuitive and unobtrusive computing companion to the user. Mobility can be improved in many ways with creative packaging, better power management, and alternative input and output devices. Wearable computer is not new, but is becoming more mainstream, and more viable these days with the newer technologies, like smaller and lower power processors, tiny powerful peripherals, ubiquitous wireless data networks, and advances in flash memory and other storage devices.

2.1 Augmented Reality

Augmented Reality (AR) is a growing area in virtual reality research, and is commonly applied as an interface between wearable computer and its human counterpart. The rise of AR is due to the fact that the real world provides a wealth of information that is difficult to duplicate in a computer. This is evidenced by the worlds used in virtual environments as presented in computer games, and visualization programs. They are gross simplification of the real environment. An augmented reality system, on the other hand, generates a composite view for the user. It is a combination of the real scene viewed by the user and a virtual scene generated by the computer that augments the scene with additional information. Ultimately AR can be used to create a system such that the user cannot tell the difference between the real world and the virtual augmentation of it. To the user of this ultimate system it would appear that he is looking at a single real scene.

In order to achieve that, the computer generated virtual objects must be accurately registered (using data obtained from tracking sensors) with the real world in all dimensions. Errors in this registration will prevent the user from seeing the real and virtual images as fused. The correct registration must also be maintained while the user moves about within the real environment. Discrepancies or changes in the apparent registration will range from distracting which makes working with the augmented view more difficult, to physically disturbing for the user making the system completely unusable. An immersive virtual reality system must maintain registration so that changes in the rendered scene match with the perceptions of the user. Any errors here are conflicts between the visual system and the kinesthetic or proprioceptive systems. The phenomenon of visual capture gives the vision system a stronger influence in our perception [9]. This will allow a user to accept or adjust to a visual stimulus overriding the discrepancies with input from sensory systems. In contrast, errors of misregistration in an augmented reality system are between two visual stimuli which we are trying to fuse to see as one scene. We are more sensitive to these errors [10, 11].

Therefore since AR interface is an integral part of the wearable computer system, a multitude of challenges must be overcome in the course of implementing wearable computing applications. More details about tracking and AR interface will be given in the later chapters.

2.2 Historical Context and Fundamental Issue

Throughout history, human have been on the quest for personal empowerment. In early civilizations, when engaging in one-to-one and hand-to-hand combat, each individual (fighting with a sword) was considered roughly an equal. With the invention of the stirrup, the balance of power was tilted towards the wealthy who can afford horses and heavy armor because even a large group of unruly peasants were no match for a smaller group of mounted cavalry. However, towards the middle ages, more ordinary individuals learned the art of fighting on the horseback and therefore the playing field was levelled. This cycle has been repeating itself over again through time as in the invention of guns. Similarly this has been happening in the electronic field as well. While in the past physical arms were the signs of status and power, the weapons of this age of information is information. With the mass acceptance of desktops at work and home, computers have gone a long way to empowering the individual in their professional tasks and at play. The next step to an increase in personal empowerment is the wearable computer, which brings available information outside in the world at all times.

In fact the most fundamental issue in wearable computing is no doubt that of personal empowerment [12], through its ability to equip the individual with a personalized, customizable information space, owned, operated, and controlled by the wearer. To lesser extent, consumer technology has already brought about a certain degree of personal empowerment, from the portable cassette player that lets us entertain ourselves with music of our choice at anytime, anyplace; to small handphone with camera that allows the capturing of pictures or even video of our love ones and sends them to whoever we desire to share them with. However, wearable computing is believed to bring about a much greater paradigm shift in the near future.

The confidence in wearable computing is built upon several aspects and affordances of wearable computing, for example personal safety, tetherless operation, and quality of life. A personal safety system that is built into the architecture (clothing) of the individual can perform duties such as monitoring health and alertness of the user (for instance waking up a lorry driver who has fallen asleep on the road). With wearable computer, workers can have the freedom from the need to be connected by wire to an electrical outlet or communications line while enjoying the convenience and help from computing devices. Tetherless operation and working environment like described can improve the worker's productivity and job satisfaction. Wearable computing is capable of enhancing day-to-day experiences, not just in the workplace, but in all facets of daily life. It has the capability to enhance the quality of life for many people by providing digital entertainment and domestic help.

2.3 Hardware: Commercial and Research Systems

The first physically built "wearable computer" device was presented by statisticians Ed Thorp and Claude Shannon in 1966. It was a cigarette-pack-sized analogue computer with four buttons used by an assistant for inputting the speed of a roulette wheel. Audio output was presented as sent tones via radio to a bettor's hearing aid. The system has actually been invented in 1961 but was first mentioned in a publication by Thorp in 1966 [13], and further details were revealed in 1969 [14].

In 1978 Eudaemonic Enterprises, a company founded by a group of physicists and friends, invented a digital "wearable computer" in a shoe. Similarly, it was also used for predicting roulette wheels. In fact, this was the only known roulette machine of the time to show a statistical profit on a gambling run [15]. According to one of the inventors, Thomas Bass, their "wearable" gave the bettor up to a

44% advantage over the casinos [16], i.e. for every dollar they played, they could expect a return of as much as $1.44.

Steve Mann [8] has invented his first wearable computer in 1981. He used it to control camera equipment, flashes, and other photographic equipment. Over the past twenty years, Steve Mann continues his work on this field, building more sophisticated systems along the way as shown in Fig. 2.1.

Figure 2.1: Steve Mann's WearComps.(Image used with permission, courtesy of Prof. Steve Mann)[17]

In recent years, a number of commercialized systems appear to provide mobile, wireless technology solutions. Pioneering the commercialization of wearable computer technology, hardware and related software is Xybernaut Corporation. They provide customized solutions as well as off-the-shelf wearable computing gadgets. Some notable products are a series of 'Mobile Assistance's (MA V, MA TC, Artigo M, and Artigo L) which are designed for workers to bring along computing powers to task-at-hand and therefore enhancing productivity; XyberKids that brings the power of a desktop computer in a wearable package and is designed to boost students' rate of learning as well as to assist students with disabilities; and a generic wearable computer named Poma which is a powerful computer completed with headmount display and networking capability.

Another notable company is ViA which specialized in selling full-function wearable computer and touch displays. The company's rugged, lightweight wearable computers are used by corporations such as Northwest Airlines, Ford and GE Engine Services, Inc. for customer service, distribution, inspection and maintenance applications. Meanwhile there is also another company called CharmedIT Technology, which is a MIT Media Lab spin-off, providing affordable and configurable wearable Internet products. The company's main product, the CharmIT Kit, is a complete plug-and-run wearable system with a flexible aluminum enclosure that allows selection of different processor board and peripheral options.

Although consumer market of wearable products is gaining grounds, the main development forces of this genre of computing gadgets still stay with the research communities in various universities. MIT Media Lab researchers have developed MIThril (as shown in Fig. 2.2), a next-generation wearables research platform, for prototyping of new techniques of human-computer interaction for body-worn applications. Although the MIThril hardware platform is a combination of off-the-shelf components and custom engineered parts, it is an impressive piece of work. MIThril ventures to construct a new kind of computing environment for applications in health, communications, and just-in-time information delivery.

Besides MIT Media Lab, another well-known research group is from Carnegie Mellon University (CMU). This active group has developed a number of wearable computers, each addressing a different class of applications, including maintenance, personal assistance, empowerment for persons with disabilities, and navigational aid [19]. The diversity and variety of wearable computer systems from CMU stems from their design principle of maximizing the effectiveness of the systems by care-

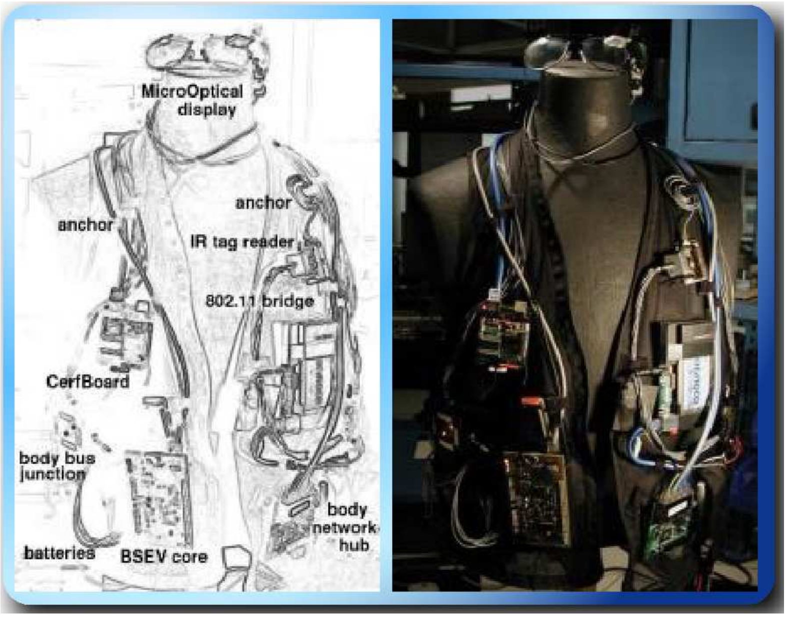


Figure 2.2: MIT Media Lab Wearable Computer, MIThril.(Image used with permission, courtesy of Prof. Alex(Sandy) Pentland, MIT Media Lab) [18]

fully matched with user tasks with the interface in the specific mobile computing environments.

2.3.1 Input Devices

Effectiveness of a wearable computer rely much on the capableness of the input devices. This is because in the real world environment, the user has often required to use one or both hands to perform a task while manipulating the input device. Thus these input devices need to be designed with this requirement in mind. Basically the traditional mouse and keyboard interfaces have to be discarded. New input interfaces for wearable computers should ideally be easily transportable, quickly accessible, easily usable in a variety of environments, and minimize interference with "real world" interactions. Over the years, various input devices have been developed. They can generally be categorized as either 'Text Input Device' and

'Graphic Input Device'.

Text Input Device

We are familiar with the QWERTY keyboard which is commonly used as a text input device. However, the QWERTY's design is not ergonomically sound especially in the context of wearable computing. This obvious dilemma, coupled with the ever rising popularity of mobile computers, has caused a surge in the research of developing alternative methods for text entry. One notable attempt to overcome poor ergonomics of QWERTY keyboards (especially when the size is reduced) is the 'soft keyboard'. Devices of this kind are claimed to be able to adjust on the fly to fit the ergonomic needs of the user. However, this ideal is often not practical in reality. Currently the popular solution is to use a stylus to tap the 'virtual keyboard' displayed on the mobile computer. Even though this input method has overcome the strain of touch typing in a small area, it introduces the problem of significantly reduced text entry speed[2].

Instead of tapping the 'virtual keyboard', some system allows the user to 'write' directly into the device. Despite the fact that modern handwriting recognition systems are not flexible enough to analyze general handwriting, these systems allow the user to 'scribble' simplified and well-described alphabet, such as Graffiti (a handwriting recognition system by Palm Corporation. With this kind of input interface, writing in place is possible and therefore the need for moving the wrist is removed and the finger work is minimized. While this input method is slower than a desktop keyboard, it is less fatiguing, and remains one of the most popular options for a mobile interface.

As for the wearable communities, another kind of input device has gained its

---

[2] With reference to [20], expert users were found to reach an average rate of twenty one words per minute (wpm) using Graffiti and eighteen wpm using the virtual keyboard. In comparison, expert keyboard typists have an average rate of sixty wpm.

wide acceptance in the recent years. It is termed ‘chord keyboard’. Chord keyboards have a comparatively small number of keys, allowing touch-typing in confined areas without reduced comfort. A chord keyboard is not as fast as a desktop keyboard for an expert, but it can achieve quite reasonable speeds for novice users, and with less training than a keyboard. The thirty six wpm (words per minute) expert speed on a chord keyboard is roughly the same as the higher end of expected speeds on most handwriting systems. Chording does have the advantage of being potentially less fatiguing than handwriting systems since there is minimal movement and no stylus needs to be held. The biggest hurdle to overcome with chord keyboards is that the keymap must be learned before it can be used, even though the alphabet can usually be learned within an hour[3]. The Twiddler2 as described in chapter two is the most well-received commercialized chord keyboard.

At the high end of the input interface is the glove-based gesture systems. These systems are also highly portable, but they suffer from excessive cost or poor accuracy. Contact gloves are affordable enough for everyday use, but they are might not be accurate enough to recognize the large number of gestures needed for text entry. There are sophisticated gloves which can sense the full orientation of the hand and is able learn to recognize enough gestures for text entry, but these are too expensive for everyday use. A prototype example is the Chording Glove [22]. This device employs pressure sensors for each finger of the right hand enabling almost all possible finger combinations to be mapped to symbols. There are additional “mode switches” along the index finger, which are used to produce more than the twenty five distinct characters. Encouraging user experiments show that rates of up to nineteen words per minute(wpm) are achieved after ten training sessions.

---

[3] This statement is taken from a testimonial given by Thad Starner, Professor at Georgia Tech and former MIT Media Lab[21].

Another extremely portable, hands-free text input interface is known as speech recognition systems. At the moment the widespread use is limited primarily by the vocabulary size and accuracy of these systems especially amidst noises and interferences. Nevertheless these are technological constraints may very well be solved in the near future. Although speech recognition is a useful text input method for simple commands (for example getting a handphone to initiate a call), there are situations in which vocal input is inconvenient or undesirable; for example, when the user is in a noisy and crowded public place, or when the user is at a meeting or seminar. Consequently, it is a good idea to back up voice input with a silent text input alternative. As it stands, a handwriting system using a simplified alphabet, speech recognition, a contact glove with a tablet, or a chord keyboard, are the text inputs most suited for use with a mobile computer. The handwriting system, speech interface, and chord keyboard are effective on a heads-up style system while conventional handwriting and the contact glove are more effective on a notepad-style system.

Graphic Input Device

With the wide proliferation of Graphical User Interface (GUI), graphic input paradigm is a familiar player in this arena. The simplest method of graphic input is by simply using an arrow key to point-and-click. This may be difficult to manipulate on certain occasions, but it allows easy pointer control at the pixel resolution and is guaranteed to work regardless of the computing environment. The performance of arrow keys can be improved by using them as jump keys in specialized applications. In addition, they are easy to implement on any computer which has room for a few small buttons and are well-suited to be used as a backup pointer control for a mobile system.

Joysticks are most useful in environments which require navigation or low precision pointing, but they are not very portable. The trackpoint is a much more portable derivation of the joystick, but the high amplification of the device makes it difficult to master. Partly due to the affordance of the device, its high performance, and successful marketing, the mouse has dominated the graphic input market and has became the de facto standard interface for a desktop environment. Unfortunately the mouse does not translate well to a mobile environment. Shrinking the mouse requires amplifying its motions, potentially causing problems similar to the trackpoint. Trackballs can be made very small, making them quite popular for use with mobile computers. While these devices work well for pointing and selection tasks, they have trouble with tasks which require use of the selection button and the trackball at the same time, such as clicking and dragging. Trackpads are slightly larger than the trackball, but are still quite portable and thus popular in many mobile systems. These devices suffer similar problems with click-and-drag to the trackball when used with a separate selection button. When used in the lift-and-tap method, click-and-drag becomes quite easy, but fine selection becomes difficult. Nevertheless there are commercial devices of this nature that are designed for wearable computing applications. One example is the Finger Trackball (Fig. 2.3).

Figure 2.3: Finger Trackball.

Touchscreens are very intuitive and easy to use, but when shrunk to a more mobile size, the finger can occlude much of the workspace, making its operation difficult. Using a stylus on a touchscreen not only solves the occlusion problem, but can be manipulated faster and with less work. Stylus-based systems also have the added benefit of being able to integrate text and graphic input, making them quite popular for handheld systems.

Intuitively eye tracking, and voice interfaces are ideal for use in a mobile environment. The primary hurdle posed by eye tracking is the poor resolution due to involuntary eye motions. Selection by dwell time may remove part of the problem, it is still so problematic that it is often easier to use a hand-operated button instead. Voice makes a very poor graphic input. A vocal system is limited to acting like arrow keys for basic cursor control or acting like function keys. There are situations where the use of vocal input are inconvenient or difficult, for example in a noisy place where background noise obscure the user's voice, or when the user wants to input data during a meeting or a lecture.

Bioelectric measurements such as EMG (electromyogram) and EOG (electro-oculogram) have much potential as a graphic interface in a mobile environment. Modern computers are fast enough to handle the computational complexity of analyzing these signals. The hardware required to measure the bioelectric signals can be made very small and the electrode connections are lightweight, safe, and barely noticeable to the user. The motions required to operate such an interface are normal body motions such as thoughts, eye movements, or hand gestures. For instance, a user with a EMG input system attached to her wearable computer can move and control the mouse by moving her eyes (for example blinking for double-click). No stylus or board needs to be held. This makes bioelectric input particularly well suited to mobile computing. However much of these are still under the realm of research projects because of our lack of understanding on the workings of our brains.

2.3.2 Output Devices

A basic design decision in building a wearable computer system is how to accomplish the combining of real and virtual in its augmented reality interface. The usual choice of output device which can accomplish such feat is a Head Mounted Display (HMD). HMDs are head-worn and are categorized into two types, namely optical and video seethrough HMD.

Optical seethrough HMD has a semi-transparent mirror (beam splitter or combiner) that reflects light beams from the computer display as well as transmitting light from the surrounding world to the user's eyes. In contrast, the video seethrough HMD uses video mixing technology to combine the image of the real world from a head worn camera with computer-generated graphics before the merged image is presented to the user in an opaque display.

The optical seethrough HMD, as the name suggests, has a seethrough lens and a small projection system, or simply has only the projection system which can be clipped onto regular glasses (as in SV-9 of MicroOptical as described in the next chapter). These HMDs work by placing optical combiners in front of the user's eyes. These combiners are partially transmissive, so that the user can look directly through them to see the real world. The combiners are also partially reflective, so that the user sees virtual images bounced off the combiners from head-mounted monitors. This approach is similar in nature to Head-Up Displays (HUDs), commonly used in military aircraft, except that the combiners are attached to the head. Thus, optical seethrough HMDs have sometimes been described as a "HUD on a head" [23]. According to Ronald Azuma [10], conceptual diagram of an optical seethrough HMD is as shown in Fig. 2.4.

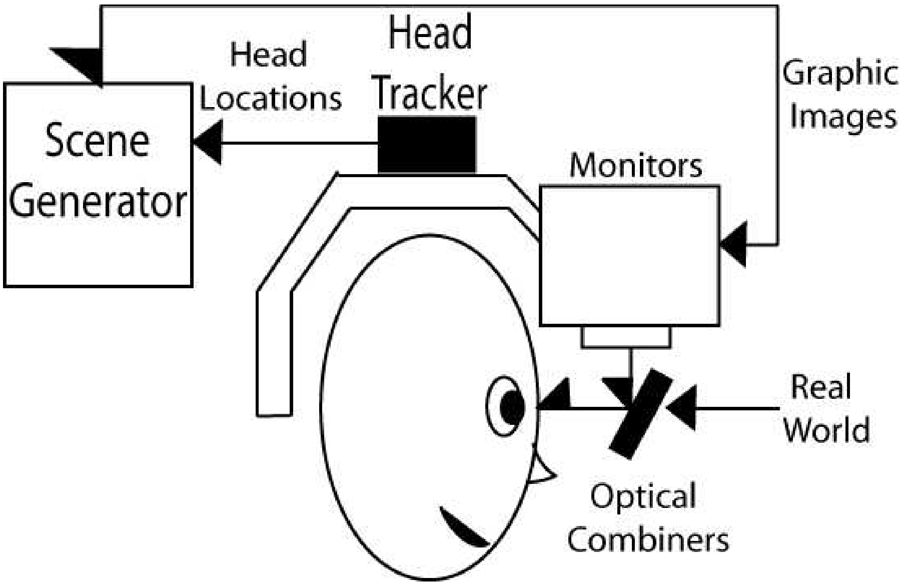


Figure 2.4: Conceptual Diagram of an Optical Seethrough HMD.

The optical combiners usually reduce the amount of light that the user sees from the real world. Since the combiners act like half-silvered mirrors, they only let in some of the light from the real world, so that they can reflect some of the light from the monitors into the user's eyes. For example, the HMD described by Holmgren [24] transmits about 30% of the incoming light from the real world. Choosing the level of blending is a design problem. More sophisticated combiners might vary the level of contributions based upon the wavelength of light.

In contrast, the video see-through HMD uses video mixing technology to combine the image of the real world from a head worn camera with computer-generated graphics before the merged image is presented to the user in an opaque display. They work by combining a closed-view HMD with one or two head-mounted video cameras. The video cameras provide the user's view of the real world. Video from these cameras is combined with the graphic images created by the scene generator, blending the real and virtual. The result is then sent to the monitors in front of the user's eyes in the closed-view HMD. Conceptual diagram of a video seethrough HMD as depicted by Azuma is shown in Fig. 2.5. The HMD used in the wearable computer we have developed (which is described in detail in later chapters) make use of a video seethrough HMD called Cy-Visor from Daeyang, a Korean company.

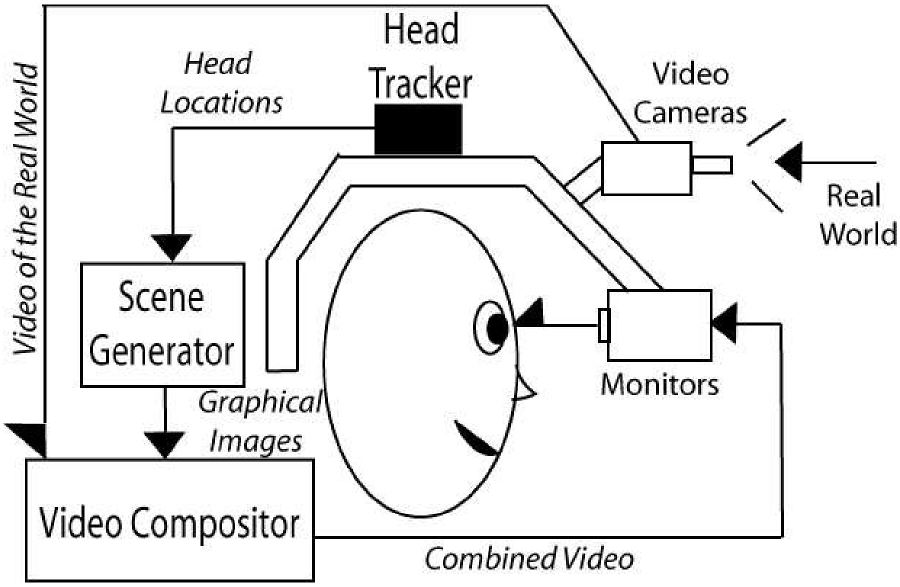


Figure 2.5: Conceptual Diagram of a Video Seethrough HMD.

There are several technical issues involving the use of the mentioned two types of HMDs. First of all, an essential capacity of HMD is to properly register the user's surrounding and the synthetic space. Thus one of the problems in achieving registration is the time lag, i.e. between the moment when the HMD position is measured and the moment when the synthetic image for that position is fully rendered and presented to the user. In fact, lag is the largest source of registration error in most current HMD systems [25], and it is typically between 60 to 180 ms. Video see-through HMDs have the potential capability of reducing the relative latencies between the 2D real and synthetic images by using memory buffers to eliminate temporal delays between the real and computer-generated images; or by delaying the video image until the computer-generated image is rendered. Optical see-through HMDs, on the other hand, have no means to introduce artificial delays to the real scene. Therefore to optimize for low latency, the users may have to limit their actions to using slow head motions.

The second problem involving the use of HMD is real scene resolution. The best real scene resolution a see-through device can provide is that perceived with the naked eye under unit magnification of the real scene. In fact, a resolution extremely close to this ideal is easily achieved with an optical see-through HMD. This is because the optical interface to the real world is simply a thin glass plate positioned between the eyes and the real scene. In the case of a video see-through, the perceived resolution of the real scene is limited by the resolution of the video cameras or the HMD viewing optics which typically have a resolution of 640x480. Further development of optical technology must be undertaken to achieve resolution that match that of the human visual system.

Another challenging issue of HMDs is to provide the user with adequate field of view (FOV) for a given application. An optical see-through HMDs typically provide from 20 to 60 degrees of overlay FOV via the half-transparent mirrors placed in front of the eyes. This may appear somewhat limited but it is good enough for a variety of applications such as medical visualization and engineering tasks. For a video see-through HMD, the FOV displayed with the opaque type viewing optic typically ranges from 20 to 90 degrees. However, in systems whereby the peripheral FOV of the user is occluded, the effective real world FOV is often smaller than in optical see-through systems.

In summary, optical see-through systems offer an essentially unhindered view of the real environment. These systems also provide an instantaneous real-world view that assures the synchronization of visual and other perceptive information. Video see-through systems, in comparison, surrender the unhindered view in return for improved ability to see real and synthetic imagery simultaneously. Therefore in choosing the appropriate HMD for an application, these tradeoffs must be considered carefully.

2.3.3 Sensors and Tracking Devices

In order for any digital system to have an awareness of and be able to react to events in its environment, it must be able to sense the environment. This can be accomplished by incorporating sensors, or arrays of various sensors (sensor fusion) into the system. Sensors are devices that are able to take an analog stimulus from the environment and convert it into electrical signals that can be interpreted by a digital device with computing power. The stimulus can be a wide variety of energy types but most generally it is any quantity, property, or condition that is sensed and converted into an electrical signal [26].

In general, there are two kinds of sensors: active and passive. The characteristics of these two types of sensors will impact their potential use as components of a wearable computer system. Active sensors require an external power source or excitation signal in order to generate their own signal to operate. The excitation signal is then modified by the sensor to produce the output signal. Therefore active sensors consist of both a transmitting and receiving system. Examples of such sensor are the thermistor, the inertia sensor, and the accelerometers. In contrast, passive sensors directly convert stimulus energy from the environment into an electrical output signal without an external power source. Passive sensors consist only of a receiver. Typical passive sensors include infrared motion detector, Global

Positioning System (GPS) receiver.

GPS is the most common method for position tracking in an unprepared outdoor environment; it is based on satellite signals. This is because of its high positional accuracy, wide geographical signal coverage, and ready availability. The GPS and its Russian equivalent, Global Orbiting Navigation Satellite System (GLONASS), are now widely used for many positioning applications, such as car navigation system and tracking of aircrafts.

The GPS is a large-scale, time-frequency tracking system. The GPS uses 24 satellites arranged in orbit such that four satellites can be “seen” from any point on the earth at a given time. In addition, there are six monitoring stations, four ground antennas, a master control station, and a backup master control station [27]. The accuracy of the atomic clock is critical because a clock error of 1 ms can produce a horizontal measurement error of 300 km [27]. The master control station controls the orbit of the satellites and corrects the clock for each satellite as needed.

Theoretically, the system can determine the position of a user with a GPS receiver by receiving a signal from at least three satellites and computing the time of arrival of the respective signals. In practice, however, the GPS receiver clock has an unknown bias. Therefore, four signals from GPS satellites must be received, from which it is possible to determine the position of the receiver and the clock bias. The GPS has an accuracy of approximately 10 meters. The main drawback of the GPS system is the inability to locate the receiver without a direct line of sight to the satellites, thus making it unusable indoor. Furthermore in an urban city with many tall buildings (urban jungle), much of the sky will be occluded which leads to the loss of satellite visibility. Another problem is the multipath distortion resulting from reflections of the GPS signal from nearby high-rise structures. Despite of all mentioned shortcoming, a precise system for the overall scale of operation is developed to improve on the accuracy of GPS tracking systems. This system is known as the differential GPS, which uses emitting ground stations that refine the resolution to the order of one-tenth of a meter [27].

Besides knowing the user's location and his environment (long range localization, i.e. the determination of location over a wide area, as provided by GPS tracking system), the wearable computer system also needs to supply information about which part of the environment is within his view so as to augment the correct virtual information. In other words, the position and the orientation of real objects in physical space must be recorded in order to maintain spatial consistency between real and virtual objects. Basically this requires the system to track the user's head movement and its orientation. Orientation information includes the yaw, pitch and roll (refer to Fig. 2.6) are essential.

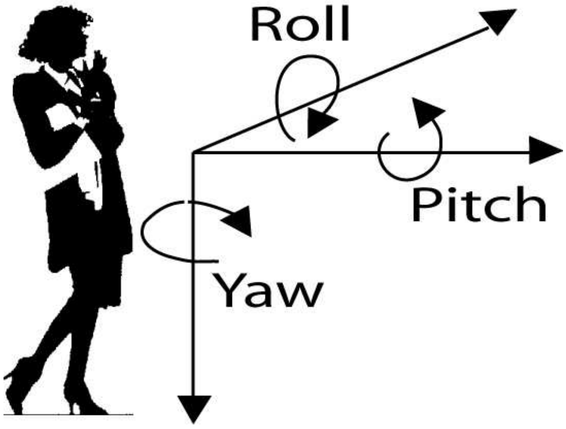


Figure 2.6: Referential Commonly Employed in Virtual Reality and Augmented Reality.

Few trackers can meet this specification (certainly not the GPS tracking system), and every technology has weaknesses. Some mechanical trackers are accurate enough, although they tether the user to a limited working volume. Magnetic trackers are vulnerable to distortion by metal in the environment, which exists in many desired AR application surroundings. Ultrasonic trackers suffer from noise and are difficult to make accurate at long ranges because of variations in the ambient temperature. Optical technologies [28, 29] have distortion and calibration problems. Inertial trackers drift with time because of the need to integrate rate data to yield position; any small constant error increases without bound after integration. Inertial sensors are thus mostly unsuitable for accurate positioning over an extended period of time. Future tracking systems that can meet the stringent requirements of AR will probably be hybrid systems [10, 30, 31], such as a combination of inertial and optical technologies [32, 33]. Using multiple technologies opens the possibility of covering for each technology's weaknesses by combining their strengths. For example in the instance of outdoor systems, usually sourceless inertial sensors that consist of rate gyroscopes and linear accelerometers are used (as in the system developed as described in later chapters).

Therefore the sensors used in our systems are mainly hybrid sensors (with the exception of the GPS receiver). One of the sensor that we have relied on for orientation tracking is the InertiaCube2, which is a inertial sensor system. Inertial sensors, as the name suggests, base their measurement upon inertia of objects. Inertia is defined as the property of matter which manifests itself as a resistance to any change in the momentum of a body [34]. Therefore, an inertial reference frame is a coordinate system in which a body does not experience a change in momentum. In an inertial coordinate system, the mass of an object is determined according to Newton's Second Law, as opposed to the Newton's Law of Gravitation. Inertial sensors use physical phenomena to measure acceleration and rotation relative to the inertial reference frame of the earth. These measurements are integrated once (or twice, for accelerometers) to yield position. The coordinate systems of these sensors are not inertial, due to the changing accelerations (centripetal or linear) of their frame of reference. However, inertial tracking systems are composed of inertial sensors, whose data can be used to determine the absolute position and orientation of an object.

2.4 Software Applications

Wearable computing can be seen as a new embedded system application. Ideally, processors will operate reliably in relatively hostile environments with minimum power consumption. Many of the new applications of wearable computing are safety-critical, for example, military and medical applications. Apart from this, wearable computers have been suggested for many other uses: to aid inspection and maintenance workers, for navigation (e.g., for blind users, tour guides), for communication (e.g., military operations, remote collaboration), as memory aids in everyday life [35], and for entertainment. Some of the fields mentioned will be described briefly in this section to give the reader a flavor of the huge potential in wearable computing applications.

2.4.1 Soldier Battlefield Applications

Future military operations are expected to occur in complex and urban environment. In this type of surroundings, it is difficult to plan and coordinate group member activities. The difficulties are further compounded by the need to minimize the number of civilian casualties, friendly fire, and the amount of damage to civilian targets. A promising solution to these problems is the emerging technology of wearable computers and augmented reality. With the use of wearable technology, accurate tracking of soldiers and supplies is possible, therefore improving the safety and performance of soldiers in the field, and communications in general. A soldier with a wearable computer can perform computing tasks while walking or otherwise moving around. His perception of the environment is enhanced by superimposing virtual objects and graphics onto the his field of view. Virtual objects that can appear in the augmented reality view may include:

- Guidance: virtual objects or arrows that guide a soldier to his goal point.
- Warnings: such as enemy locations, sniper locations, mines, enemy tank locations, enemy infrastructure locations.
- Automatic electronic identification of friendly forces and visual feedback information in the form of virtual object tagging.
- Virtual map and virtual viewing such as see through maps for jungle or dense locations.
- Hidden infrastructure and utilities such as electric lines, service tunnels, subways, and building floor plans.

One important military system is a joint research project between U.S. Defense Advanced Research Projects Agency (DARPA), and Carnegie Mellon University. They are developing a wearable maintenance assistant to help soldiers respond to unexpected events in the field. As a matter of fact, since 1992 DARPA has been supporting research on HMDs and other AR-enabling technologies. Also the U.S. Army has similar projects on developing military wearable technology. They have launched the Land Warrior Program since 1997, which hopes to develop wearable computers as standard equipment by 2008.

The Naval Research Lab (NRL) of U.S. government has also developed a similar system - the Battlefield Augmented Reality System (Fig. 2.7) - to help soldiers during military operations in urban environments. The system goal is to augment the environment with dynamic 3D information (such as goals or hazards) usually conveyed on 2D maps. Recently, the system also provides tools to author the environment with new 3D information that other system users see in turn [36].

Figure 2.7: Battlefield Augmented Reality System. (Photograph used courtesy of Naval Research Lab)
Downloaded from: http://www.ait.nrl.navy.mil/vrlab/projects/BARS/images/barsII.JPG

2.4.2 Medical Applications

Medical applications are one of the traditional implementation area of AR system. The first clinical medical experiment with AR is being conducted at the University of North Carolina at Chapel Hill [37]. Instead of the radiologist's usual practice of looking up at a sonogram screen and then back again at the patient, ultrasound images are seen through the physician's headgear as projected directly onto the patient's body. This provides a sort of virtual X-ray vision throughout the procedure. Breast lumps and other possibly cancerous anomalies show up as ghostly white outlines against an uneven gray background. And the position and orientation-sensing technology in the HMD lets the radiologist "see" where to guide a biopsy needle with unprecedented precision. The hoped-for outcome of this AR application includes fewer complications and shorter recovery times for existing procedures, as well as the development of new surgical techniques.

Presently, wearable technology has progressed into the hospital as well. The technology can be applied to increase the accuracy and level of detail of the patient information available to the doctors [38]. Also, fully documented medical histories of patients become immediately available in an accessible and reliable medium upon the request of the doctors. On the other hand, for the patients, wearable computers will allow unobtrusive continuous monitoring of their ailment for precautionary or even preventive measures. For example in a project lead by Bonato [39], wearable computers are used to monitor patients with muscular complaints during activities of daily living. These computers have sensors that record physiological variables (EMG, heart rate) of the patients. The researchers hope by studying the biopsychosocial mechanisms in stress-induced muscular pain, they may better understand the pathogenesis of muscular aches with a view to treatment and develop biomarkers to recognize and avoid hazardous situations.

One recent project managed by Xybernaut [40] and members of PARREHA Consortium (an organization founded by Parkinson's researchers from France, Germany, Greece, Italy, Spain and the United Kingdom) aims to study how advanced computing technologies could offer benefits to Parkinson's disease patients [41]. The subsequent clinical research shows that certain types of visual information (also referred to as visual cues) presented over the AR interface of the wearable computer, when combined with human sensory data, greatly enhanced patients' coordination while walking. The wearable computer system has enhanced patients' awareness, motor skills and coordination - specifically related to walking. To-date, this integrated wearable computing solution has been utilized for approximately one year with compelling results.

Another medical project, managed by the researchers at Carnegie Mellon University (CMU), is named DiMA (Diabetes Management Assistant) [42]. It is a wearable computer system with wireless communication and a set of accessories that are designed to help diabetic patients and their doctors to better manage the disease by focusing on several daily activities such as diet, exercise, and medical monitoring of the disease.

CMU apart, there is another renown lab in augmented reality field that has engaged in medical applications. It is the Human Interface Technology (HIT) lab from University of Washington. Researchers there couple an expert system with multimodal input in a virtual environment to provide an intelligent simulation tool or surgical assistant [43]. They have produced a prototype sinus surgery interface which is capable of monitoring the user's progress in the surgical procedure, provide automatic feedback, respond immediately to multimodal commands for navigational assistance and identification of critical anatomical structures.

2.4.3 Manufacturing Applications

Besides medical applications, another traditional area of research in wearable AR systems is the assembly applications. In fact, the term “augmented reality” was coined at Boeing in 1990 by researcher Tom Caudell who was asked to come up with an alternative to the expensive diagrams and marking devices then used to guide workers on the factory floor. He and his colleague, David Mizell, proposed replacing the large plywood boards, which contained individually designed wiring instructions for each plane, with a head-mounted apparatus that would display a plane’s specific schematics through high-tech eyeware and project them onto multi-purpose, reusable boards. Instead of reconfiguring each plywood board manually in each step of the manufacturing process, the customized wiring instructions would essentially be worn by the worker and altered quickly and efficiently through a computer system. Currently the idea is realized at the factory floor of Boeing (although it is still not deployed at the time when this thesis is written). By using AR, the mechanic is guided step-by-step through a disassembly procedure by his wearable computer system, thus is able to reduce errors and risks while increase productivity and knowledge.

Assembly line aside, wearable technology helps workers to perform their task more efficiently at the field too. Xybernaut [44] provides such solutions to a number of their industry partners. One of them is Bell Canada. In 2000, the company has developed light and mobile computers for the field workers of Bell which help them in technical repair works. In the trial, these technicians saved more than 50 minutes a day, thereby decreasing the response time for customer-service calls and increasing the number of orders they could complete in a day.

2.4.4 Navigation and Tracking Applications

The first outdoor navigation and tracking system was the Touring Machine [45]. Developed at Columbia University, this self-contained system includes tracking (with a compass, an inclinometer, and a differential GPS), a mobile computer with a 3D graphics board, and an optical seethrough HMD. The system presents the user with world-stabilized information about an urban environment (the names of buildings and departments on the Columbia campus). The AR display is cross-referenced with a handheld display, which provides detailed information. More recent versions of this system render models of buildings that previously existed on campus (as shown in Fig. 2.8), display paths that users need to take to reach objectives, and play documentaries of historical events that occurred at the observed locations. Another similar project which has recently been started is called Archeoguide. It aims to develop a wearable AR system for providing tourists with information about a historic site in Olympia, Greece [46]. This system allows the user to access information in context with the exploration of the site through position and orientation tracking. It also caters to provide personalized and thematic navigation aids in physical and information space through the use of visitor and tour profiles by taking into account cultural and linguistic background, age and skills. More importantly, the users can enjoy the visualization of missing artefacts in 3D and reconstructed parts of damaged sites on their HMDs. Furthermore multi-modal interaction for obtaining information on real and virtual objects through gestures and speech is supported.

Figure 2.8: A View Through a SeeThrough HMD Shows a 3D Model of Demolished Building at Its Original Location. (Image used with permission, courtesy of Prof. Steven Feiner, Computer Graphics and User Interface Lab, Columbia University.)

2.4.5 Entertainment Applications

Before the emergence of wearable computer gaming applications, augmented reality game research has gotten a head-start with systems such as AR2 Hockey [47]. In this game, two users are allowed to hit a virtual puck on a real table where they can see each other through a HMD. AR2 Hockey represents a collaborative AR system whereby two or more people can share a spatially- and temporally-coordinated virtual space with a real space. In other words, the players share a physical game field, paddles, and one virtual puck. As the game began, the players communicated with one another through the mixed space, allowing real-time, accurate registration between spaces and players.

Shortly after that, another AR game is developed and is called AquaGauntlet [48] (Fig.2.9). It is a multi-player game where players fight with strange invaders coming from the virtual world through some egg-shaped objects into the physical game space. Some technical improvements found in this game as compare to AR2 Hockey include allowing more than three players to participate; achieving occlusion between real and virtual objects; producing spatial sound effects; and accepting action commands by means of gesture. To achieve these marvels, more sophisticated hardware is used. For instance, magnetic sensor for detecting head position, and cameras for capturing the scene in front of the player, are placed inside each HMD. Also, inside the gun, there are magnetic sensors for detecting hand movements, and a vibrating motor for giving the sense of a gun kickback. Hardware aside, environmental mapping technique is used to render each virtual invader object in such a way that each surface reflects the images of the real environments. Thus, occlusion of virtual invaders is obtained when they are hidden by real objects. Shadows of virtual invaders are casted on the real objects too to maintain visual consistency between the real and virtual worlds.

Figure 2.9: AR Game: AquaGauntlet. (Image used with permission, courtesy of MR Systems Laboratory , Canon Inc.)

But the true AR wearable computer entertainment was pioneered by AR-

Quake [49] where a single player would move around in the physical (indoor/outdoor) world while shooting at virtual monsters. In this game, the view inside the player's HMD is determined solely by the orientation and position of the her head. The game is controlled using easy to understand real-life props, such as a plastic gun with simulated recoil, and metaphors, i.e. using the gun to shoot at the virtual monsters. The gun is connected to a Tinmith outdoor backpack computer via interfacing hardware. This backpack computer system comes with DGPS sensor for tracking the user's position, and a digital compass for obtaining the user's orientation.

Besides ARQuake, a slightly different wearable computer entertainment project named "Pirates!" [50] was developed. It pioneered a new field termed social computer game research. In this game, multiple players, carrying PDAs with proximity sensing technology built-in, move around a room area for interaction among one another. The player's contextual information (such as the physical co-location of players and objects in the world into the game context) is incorporated as an important element of the game mechanics.

Another important project in wearable computer entertainment is a game board detailed in E3 project [51]. This game examines the essential elements of free play, such as spontaneity, physical cues, awareness information and multi-user social interaction. The game environment consists of a tabletop display system with a custom sensor interface. The game board is a projected map, tessellated into a grid of 20 by 30 hexagons. Each hexagon represents a space that the characters are allowed to occupy and is one of four terrain types: water, plains, forest, and mountains. The players have to discover their teammates by physically moving about, look for clues in hidden holders, and then solve the puzzles exchanging clues and information with other players conversationally in the physical world.

Another active group investigating mixed reality gaming is the Mixed Reality Lab from University of Nottingham. They have recently developed a game named “Can You See Me Now?” [52]. In this project, the researchers attempt to establish a cultural space on common handheld electronic devices, such as handphone and pda. They allow the public to play the game on the streets, as well as online, using their own devices. These players share the same “space” with the overlay of a real city and a virtual city.

Chapter 3

Hardware Development of Wearable Computer

It is a common misconception of the man-on-the-street that wearable computer is a small version of desktop, i.e. it is rectangular in shape, uses miniature mouse and keyboard as input devices and uses standard operating systems and software. The truth is since wearable computer is built upon the notion of merging the user's information space with his or her work space. It must blend seamlessly with existing work environments, thus providing instantaneous responsiveness as well as intuitive operation. This level of personal computing calls for detail identification of effective interaction modalities and accurate modelling of user tasks in the supporting software, which can hardly be provided in actuality by bulky, stationary, and passive desktop computers. Therefore conceptual frameworks are developed to bring forth the criterion changes necessary for the realization of a successful wearable computer.

3.1 Design and Construction of Wearable Computer

While a drastic paradigm shift from the familiar desktop is anticipated, it is important that conceptual integrity in design is maintained at all time. First consideration in the design phase of wearable computer is wearability, i.e. fitting well on peoples bodies. This is difficult because human bodies are of soft organic shapes and are almost constantly in motion; while the internal components to any computer are in hard rectilinear shapes and are rigid in form. Another difficulty in striving for wearability is minimizing the weight of wearable computer. Housing decisions will determine the size and weight of the final device, which in turn are primarily fixed by the power requirements of the device and this, in turn, is decided upon the electronics used.

Second factor affecting the design of wearable computer is usability. Since wearable computers are used for the most part in assisting humans in tasks involving, intensive, real time interaction with the environment, for example equipment maintenance, search and rescue operations, surgery, security surveillance, and e-ducation; it is imperative that a wearable system is easy to use, with largely hands free user interface. In most cases a head mounted, eyeglasses like, see-through display is necessary to allow computer output to be integrated into the users view of the environment. The system should have an array of sensors for gathering context information about the environment and the user activity. It also needs a high performance wireless network interface for Internet access and teleconferencing.

In this chapter, prior experiences leading up to the development of the final version of wearable computer code-named "DSTAR" are described. After that, components of DSTAR are studied in detail. Lastly, various technical problems and limitations are identified so that plausible solutions can be developed in the future.

3.1.1 Prior Experiences

Prior to the development of DSTAR wearable computer, I have explored two intriguing system configurations in an attempt to gain deeper insight to the various aspects of wearable computer design. The first wearable computer, named MatchboxPC wearable computer [53], is designed with maximum wearability in mind. The second wearable computer, named Espresso wearable computer [54], is constructed to explore usability of tiny-sized computer with full desktop computing power.

The main reason behind which the MatchboxPC board (as in Fig. 3.1) from TIQIT corporation is chosen as the single board computer (SBC) in the MatchboxPC wearable computer system is its tiny size. It is in fact one of the smallest SBC that is available in the market. It has a mere dimension of 7x5x2.4 cm; and a weight of 93 gram. Furthermore, it has a good video chip that is able to display SVGA resolution up to 256 colors.

This miniscule computer fits well in a small waist pouch together with its battery (it has a built in dc-dc converter supporting a 7.2 volt camcorder battery or 4 AA common Nicads batteries in series input) and its expander board, which has keyboard, VGA, serial and parallel ports, ethernet, and floppy connectors. Twiddler2 from Handykey Corporation [55] is chosen as the input device (further details on this device will be discussed in the following section); and SV-9 viewer from MicroOptical Corporation [56] is chosen to be the output display(as in Fig. 3.2).

MicroOptical's Head Mounted Display (HMD) provides a hands-free, and port-

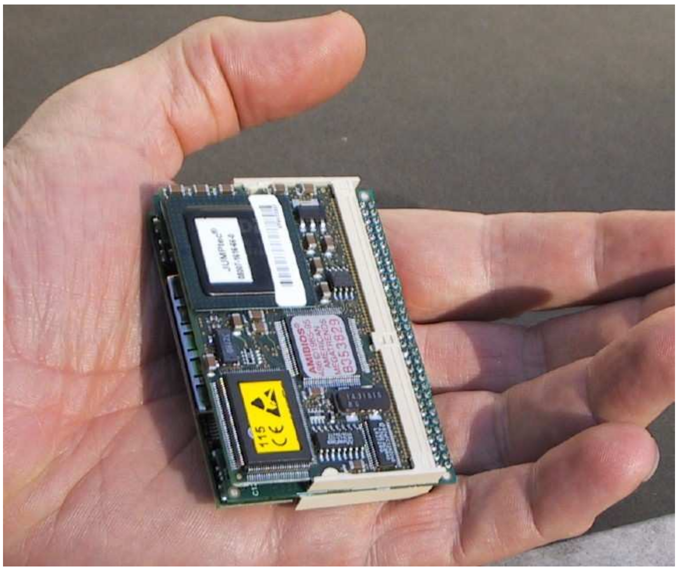


Figure 3.1: MatchboxPC Single Board Computer.(Image used with permission, courtesy of Vaughan Pratt (chairman & CTO, Tiqit computers, Inc.).)

Figure 3.2: MicroOptical Head Mounted Display. (Image used with permission, courtesy of MicroOptical, Inc.)

able computer output display. Being one of the smallest, lightest and most ergonomic displays in the market, it is well-suited for mobile and wearable applications as it allows users to put text, graphics and video images continuously in their field of view while maintaining their non-immersive real world view. Furthermore it offers a color depth of 24 bits (16M colors), and is mountable to safety or conventional eyewear. It can be used for left or right eye viewing and has a built-in focus mechanism. With the pixel format is 640 columns by 480 rows, it is compatible with most computers and instruments that provide a VGA signal at 60 Hz (in this case the MatchboxPC).

The whole MatchboxPC wearable computer system configuration is shown in Fig. 3.3. The HMD is connected to the MatchboxPC via a D-sub 15pin connector, the same connector that is used to connect PC monitor to the CPU. The Twiddler is connected to the PS2 port on the SBC extension board. A Sony Lithium-Ion battery (video camcorder battery) is connected to the SBC as a power source. The HMD, however, is powered up by a seperate 9V battery.

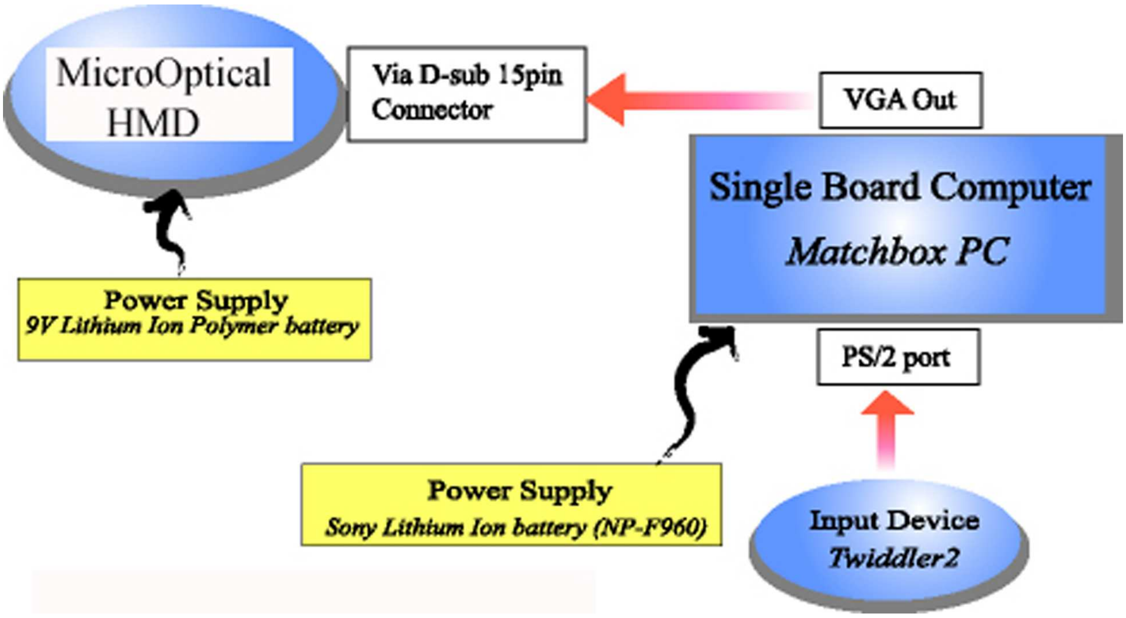


Figure 3.3: MatchboxPC Wearable Computer System Configuration.

However there are three main problems to this system: (1) computing power, (2) storage and memory capacity, and (3) expendability. The MatchboxPC incorporates a 66MHz 486-SX CPU from Advanced Micro Devices, 16 MB of RAM, 512K video system for SVGA graphics, and a 1GB IBM Microdrive hard disk [57]. The machine is slow although it's nearly silent since there is no room for a fan. Microsoft Windows 95 runs reasonably well; but Windows 98 is operating at a strain. Running of large programs, such as Microsoft Visual C++ compiler, is completely out of the question given its memory limitation. Furthermore, its expander board has only one parallel port and two serial ports (out of which one is used for attaching a serial mouse since the only PS2 port is used for a keyboard). This makes connecting sensors to the board difficult. The problem of expendability is exacerbated by the lack of optional accessories such as USB (Universal Serial Bus) port, PC104, PCMCIA (Personal Computer Memory Card International Association) slot et cetera, thus attaching additional devices such as graphic card, and Wireless LAN card is not an option. All these problems lead to severe limitations in software application development: typical wearable computer applications involving tracking, navigation and augmented reality interface cannot be realized.

Turning away from the MatchboxPC wearable computer, I experiment with another miniature computer that has most of the standard PC hardware and software support: Espresso PC. The SBC inside has an Intel Socket 370 CPU Intel Celeron. It has a 512KB of Flash ROM as its BIOS, and one SDRAM slot on board which supports up to 256 MB of memory. There is good video and sound support on the board with a built-in Full Motion Video Accelerator with 4 MB of shared memory, and built-in sound with microphone jack. The whole Espresso PC is of a size similar to that of a 3.5 inches hard disk, and weighs less than 500 grams. The detachable Docking Station, which connects to the main computer via a built-in proprietary AGP interface, offers a floppy drive and a CD-ROM drive. Espresso PC also has all standard I/O ports, which include a built-in touch pad, a parallel port, a serial port, and two USB ports for USB devices.

One of the initial problems of using Espresso as a wearable is power supply. It doesn't come with a built-in battery pack like one that is commonly found in laptop.

Needing 15V 3A power, I have opted to use PowerPad 160 from Electrovaya [58] which is originally designed to supply lasting power (about 12 hours) to laptops with maximum capacity of 15V 11A 160Wh. It is making use of Lithium Ion SuperPolymer technology to provide more power by volume and weight than any other commercial battery, i.e. with higher energy density than other commercially available batteries.

The configuration of Espresso wearable computer is shown in Fig. 3.4. Basically the HMD is connected to the Espresso via a D-sub 15pin connector, the same connection that is used to connect PC monitor to the CPU. The earphone port on the Espresso is connected to the Stereo audio jack on the Cy-Visor (HMD described previous chapter). The video camera is connected to the USB port on the SBC. The Twiddler is connected to the PS2 port on the SBC. Power Pad 160 is connected to the SBC as the power source. The HMD, however, is powered up by a separate 9V power supply.

Although with Espresso PC, additional devices needed for wearable computer applications such as sensors can be connected, there is an unforseen complication: MicroOptical HMD cannot be used as output display for this wearable computer probably due to hardware incompatibility which leads to synchronization failure. Thereafter, I use another HMD, Cy-Visor by Daeyang (details of the HMD will be discussed in the later section), as the output display. Being a type of video-seethrough HMD, I need to attached a camera to Cy-Visor for video capturing of the real world in augmented reality based wearable computer applications. I have used a common USB webcam for this purpose. Much to my dismay, however, the graphics processing power on Espresso is hugely insufficient for processing virtual objects overlaid on the video stream from the camera. This wearable computer is nevertheless able to support simple text overlaying tracking and navigation ap-

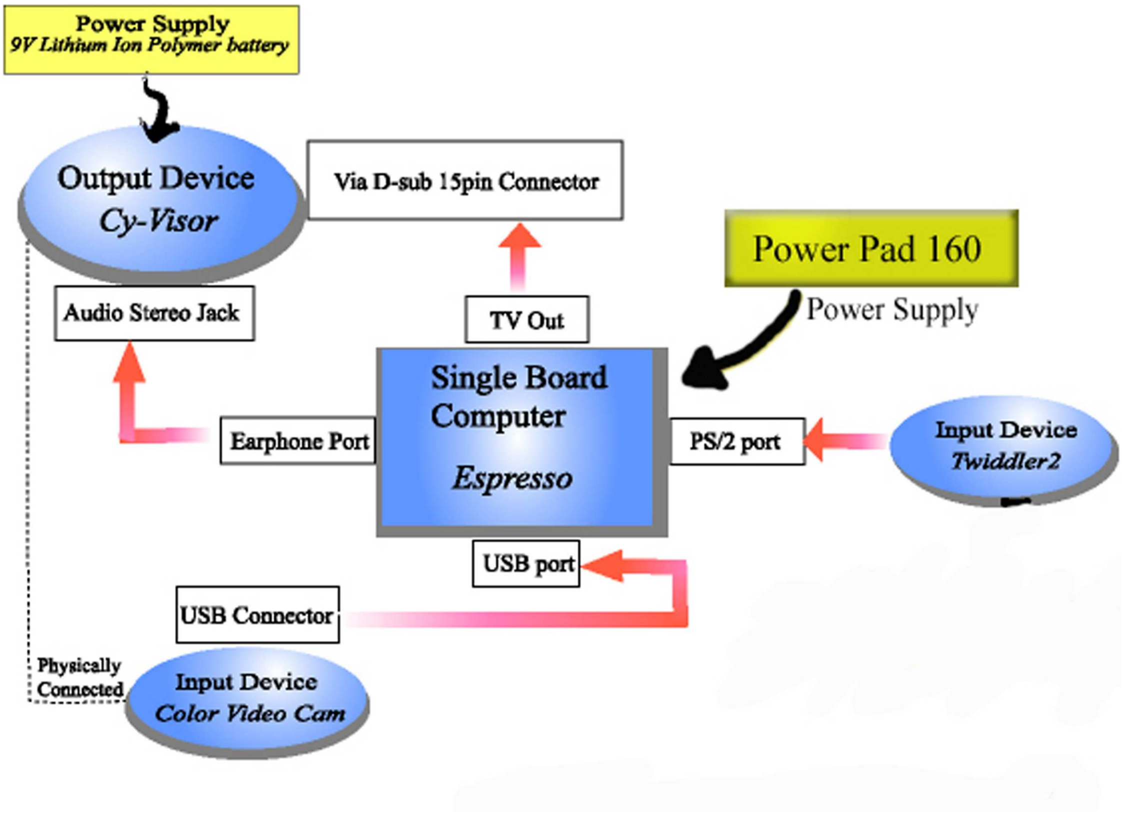


Figure 3.4: Espresso Wearable Computer System Configuration.

plications. In order to expand the scope and complexity of wearable computer applications, I choose to compile another wearable computer with much higher computing power, expandibility, and flexibility.

3.1.2 DSTAR Wearable Computer

3.2 Hardware Design Details

As mentioned before, the wearable computer built must be ergonomically comfortable, and physically secure. The main concerns are to provide the users with tetherless operation for maximal mobility, and multisensory support for environmental attentiveness and awareness. In this section, details about the physical fabrication and assembly of the system will be described. Top level technical design is discussed. Then I will attempt to estimate the power consumption of the whole system. Lastly, problems encountered during the hardware designing phase are presented.

3.2.1 Fabrication of Wearable Computer System

DSTAR is designed with powerful performance in mind. Its high level configuration is as shown in Fig. 3.6. Accordingly, the wearable computer is assembled as shown in Fig. 3.5. The main components of the wearable computers are Transmeta Single Board Computer (Tiny 866ULP from Advanced Micro Peripherals Ltd running on Crusoe processor), Twiddler2, Cy-Visor HMD with FireWire camera attached, two Sony F960 InfoLithium batteries or alternatively Power Pad battery pad, InertiaCube2 (inertia sensor from InterSense), DRMIII module (GPS and Dead-Reckoning device from Point Research Corporation), and TDK Bluetooth device. Details about the various components are described in the following paragraphs. Note that alternatively I also use another motherboard with the same form factor, 786LCD/3.5" SBC from Inside Technology, which has a Pentium 4 CPU onboard.

The Fig. 3.7 shows the exploratory DSTAR wearable computer in action with the author donning the wearable computer. Initially the InertiaCube2 is attached to a cap, but I have modified the arrangement later to attach it to the HMD instead. This arrangement provides better stability and hence accuracy in tracking because the cap is often moved unintentionally when the user is mobile. A close view of the HMD is as shown in Fig. 3.8.

As shown in Fig. 3.6, DSTAR is made up of different components. These

Figure 3.5: DSTAR Wearable Computer Components.

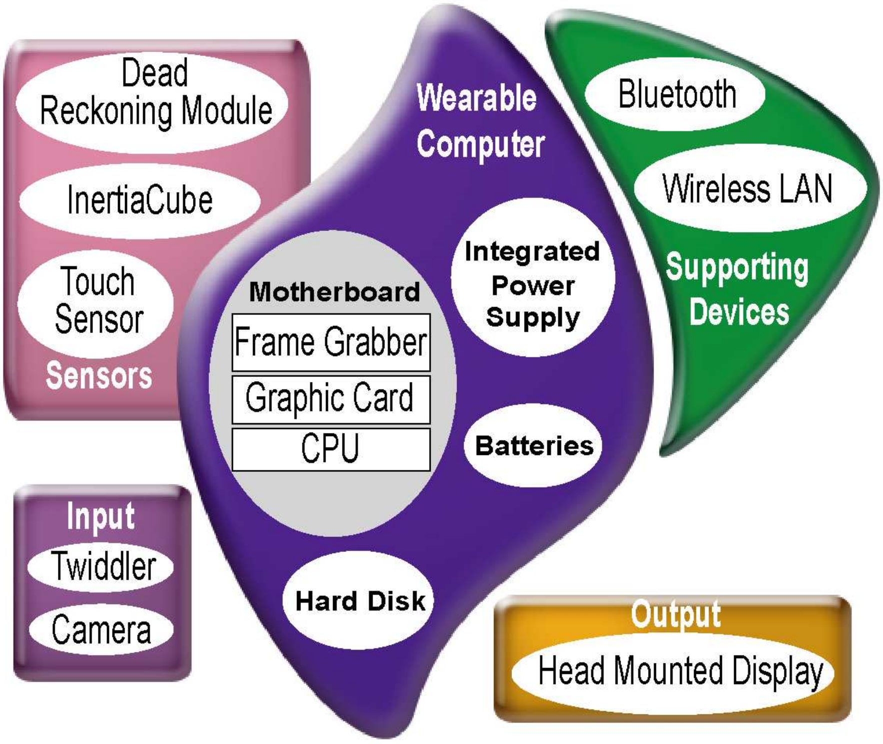


Figure 3.6: DSTAR Wearable Computer System Configuration.

Figure 3.7: DSTAR Wearable Computer as Worn by the Author.

components are connected to one another in the configuration depicted in Fig. 3.9. Although the motherboard used is of a much smaller form factor, its power requirement and functionality do not defer much from the common ATX motherboards. For external connectivity, it has two serial and USB ports. Keyboard and monitor connectors are the usual PS2 and video port respectively. However its PC104 slots are of smaller form than the standard ones. As a result of that, an additional 40-to-44 pin converter is needed to interface the board with the 2.5” harddisk used.

Figure 3.8: DSTAR Wearable Computer HMD.

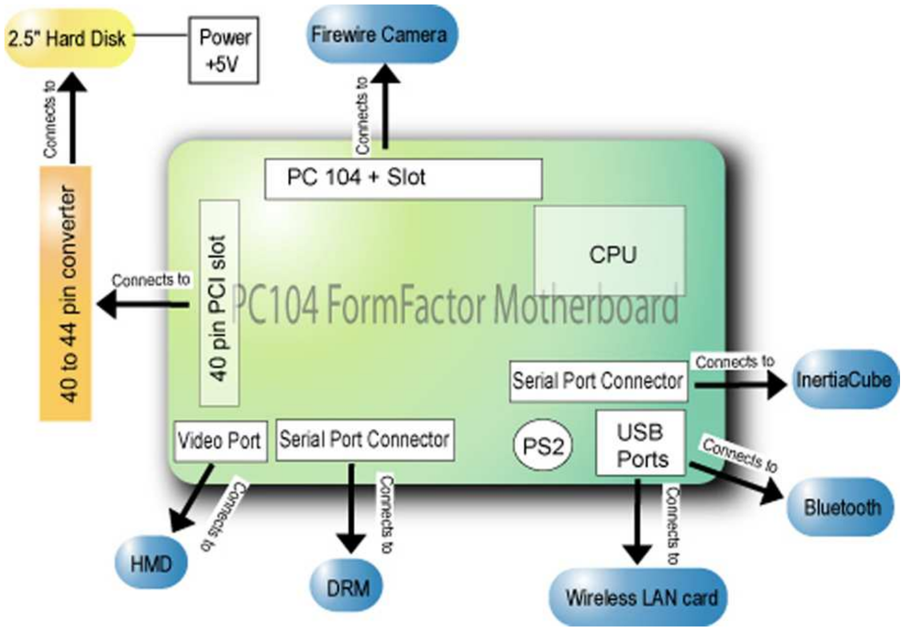


Figure 3.9: Hardware Components Inter-connections.

Since the wearable computer is used as a prototype, little attention is paid to the aesthetical aspects of the assembly. Ease of use and modification are the emphases here. As shown in Fig. 3.10, the battery pad is attached to the back of the wearable computer jacket. There are three reasons for this arrangement: firstly, the back is the part of the torso with the least physical movement for a user engaging in physical activities; secondly, it serves to balance out the weight of the motherboard and other components (twiddler, and GPS sensors) in the front pockets of the jacket; and lastly, in this way, the battery is nicely concealed instead of being draped around like a technological tumor. The alternative battery source, Sony InfoLithium batteries, are tied together and put in the back bottom pocket at the side of the power regulator.

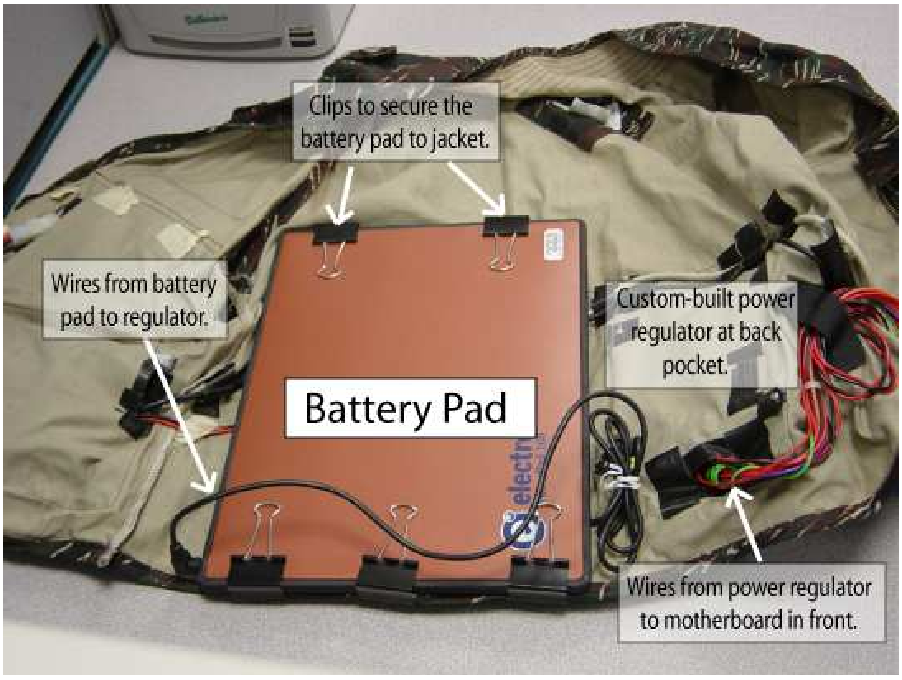


Figure 3.10: Battery Pad on Wearable Computer.

Nevertheless to maintain neatness of the design, the wiring is hide inside the jacket. As seen in Fig. 3.11, the bundle of color-coded wires is tied up and tapped to the inner side of the jacket. This arrangement makes the wearable computer more visually pleasing, easy to put on, and does not restrict the movements of the user.

Since the battery pad does not service the exact power requirements of the various components, a regulator was designed to do so. Details of the regulator are discussed in the next section. Since the regulator requires a cooling fan to maintain

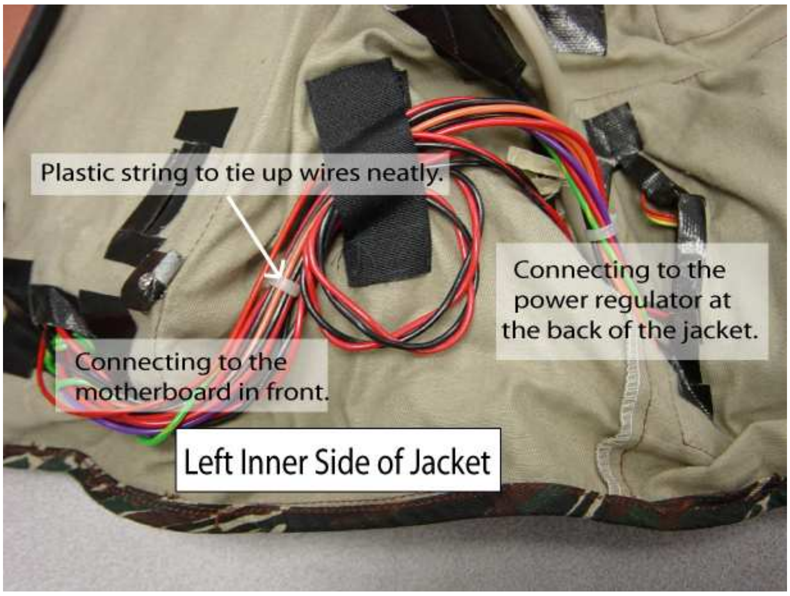


Figure 3.11: Wires are Concealed Inside the Jacket.

the temperature on board for the convertors, it is placed at the outer bottom back pocket of the jacket (as shown in Fig. 3.12) for safety and non-obstruction.

Figure 3.12: Power Regulator at the Back Pocket.

The motherboard together with the harddisk, is secured to the bottom front pocket. The sturdiness of the configuration is very important for the proper working of these two components. Movements must be minimised. This is done with the use of screws and heavy duty taps. There are various external connections to the motherboard as shown in Fig. 3.13. These connectors and wires are carefully concealed in the pocket for orderliness.

Figure 3.13: The Motherboard with Its External Connections.

Motherboard apart, two other important components on the front pockets of the wearable computer jacket are the GPS sensor and the Twiddler. As seen in Fig. 3.14, the GPS sensor is covered inside the pocket. The Twiddler, on the other hand, is placed inside the bottom front pocket when not in-use (as in Fig. 3.15).

3.2.2 Technical Design Details

After discussing the physical arrangements of the components of the wearable computer, technical specifications about the various components are given. I will present the details about the input devices, the power supplies, the sensors, and the output device.

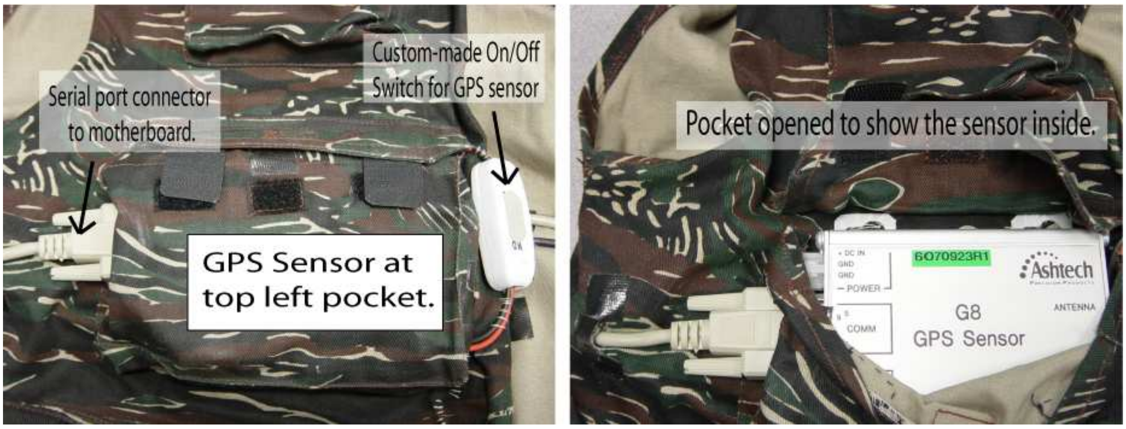


Figure 3.14: GPS Sensor.

Figure 3.15: Twiddler in the Front Pocket.

Input Device: Twiddler2 and Firewire Camera

The popular wearable computer input device, Twiddler2 [59] (as seen in Fig. 3.16), is choosen for DSTAR wearable computer. It is a pocket-sized mouse pointer plus a full-function keyboard in a single unit. It also conveniently plugs into standard keyboard and mouse ports (it has both PS2 and USB versions). Combining major innovations in pointer and keyboard technology, the Twiddler2 is designed to ease the challenges of manipulating physical input devices in the field of mobile and personal computing. The two components of Twiddler2 are descriped as follows:

MOUSE: The Twiddler2's mouse pointer is the IBM Trackpoint. The mouse pointer is controlled by the thumb, the other fingers operate the buttons in front.

KEYBOARD: The Twiddler2 incorporates a keyboard which is radically new-age ergonomic keypad designed for "chord" keying. This means that one or more keys are pressed at any one time. Each key combination generates a unique character or command. With 12 finger keys and 6 thumb keys, the twiddler can emulate with ease the 101 keys on the standard keyboard, and in addition to that, numerous user-customized commands.

Figure 3.16: Twiddler2: Keyboard and Mouse. (Photograph used courtesy of Handykey Corporation.)

The firewire camera selected is Firefly from Point Grey Research [60]. It is an OEM-style IEEE-1394 board level camera specifically designed for industrial machine vision tasks. Supporting asynchronous trigger, multiple frame rates, and 640x480 or 1024x768 24bit true color, the Firefly is not only useful in capturing and displaying video as in the wearable computer applications described in this thesis, it also has great potential in digital imaging applications. Through the

IEEE-1394 interface, the computer communicates digitally with the camera, thus allowing reliable transmission of images and software control of camera parameters.

Power: Sony F960 InfoLithium batteries and PowerPad battery

Numerous battery packs that are available commercially fulfil the power requirements of DSTAR. Nevertheless, among these batteries which come in different composition, size and runtime, the Lithium-Ion ones are one of the smallest in size and longest in runtime. I have choosen the readily available camcorder battery, the Sony NP-F960 Lithium Ion battery, for this important purpose. Its specification is shown in Fig. 3.17.

Sony Rechargeable Lithium Ion Battery Pack

NP-F960

Features:

- Built-in microprocessor accerately calculates remaining power within minutes.
- 7.2V 38.8Wh (5400mAh) with no Memory Effect.
- Up to 15 hours of continuous usage time.

Figure 3.17: Sony NP-F960 Lithium Ion battery.

The power supply board which uses the Sony batteries as source for the wearable computer is designed in the lab as seen in Fig. 3.18. With the purpose of minimizing the size of the board in mind, highly efficient switching regulators are used to provide 5V and 12V required by the SBC. A less efficient linear regulator is however used to provide 6V to the InertiaCube2 so as to prevent noise from affecting this sensitive device.

I have bundled the batteries to the power supply board. It is important that

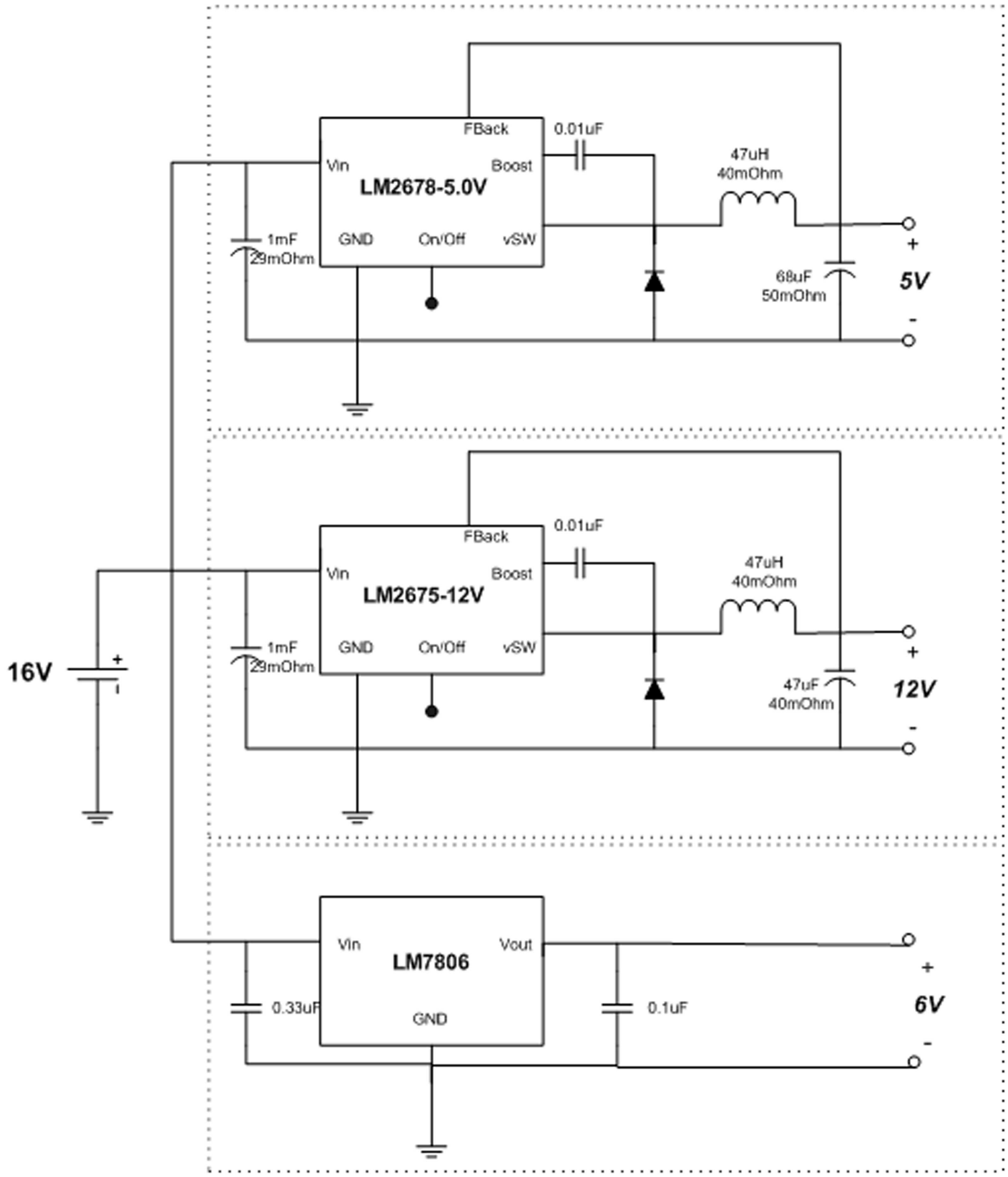


Figure 3.18: Design Schematics for Power Supply.

connection is tight and secure so as to prevent accidental power failure which might damages the main system and the accessorial sensors.

The same power regulator can be used with the alternative power source –

Electrovaya PowerPad 160 [58]. This advance Lithium Polymer battery provides more power by volume and weight than any other commercial battery. It has a compact design, and it weighs only about 1 kg.

Sensors: InertiaCube2 and DRMIII module

InertiaCube2 (Fig. 3.19) Inertial Measurement Unit (IMU) from InterSense [61] was one of the first to successfully developed human motion tracking systems based on inertial sensors. This piece of state-of-the-art equipment replaces six separate inertial instruments (gyros and accelerometers), plus their required electronics and precision mounting fixtures, with one part that is smaller than any one of the original instruments. Basically the InertiaCube2 integrates a digital smart-sensor module using micro-electro-mechanical systems (MEMS) technology and involves no moving parts. By using sourceless (i.e. self-referenced) inertial sensors as a primary means of tracking motion, it has high update rates (120 Hz), smoothness and predictive capability, and excellent immunity to most forms of external interference. This include electrical interference from wiring and magnetic interference from other nearby components/devices. In addition to sensing three angular rates and three linear accelerations, this sensor also has integral solid-state magnetometers which sense components of earth's magnetic field along three perpendicular axes. These magnetometer readings can be used as a digital electronic compass for correcting yaw drift in sourceless orientation trackers.

The DRMIII (Fig. 3.20) from Point Research Corporation [62] is an electronic module comprising of a twelve-channel Global Positioning System (GPS) receiver, digital compass, pedometer, and altimeter. The DRM measures the displacement of the user from an initialization point by measuring the direction (with data obtained from the compass), and distance traveled (using accelerometer data) with each

Figure 3.19: InertiaCube2 Inertial Measurement Unit. (Photograph used with permission, courtesy of InterSense, Inc.)

footstep taken. Although the DRM is a self-contained navigation unit, when GPS position data is available, it can be used to correct both the distance and direction calculations with the help of a Kalman filter algorithm. Besides, in conjunction with the step detection logic (pedometer), the module can detect running, sideways, and backwards walking.

Output Device: Cy-Visor HMD

Cy-Visor Head Mounted Display (HMD) from a Korea Company named Daeyang is a durable headset designed for mobile and personal computing applications. It provides full color, SVGA resolution at 800x600 (1.44 million pixels) and offers quality viewing, delivering clear text and graphics. With D-Sub 15 pin, RCA and S-Video connections, it will run with most computers for an immersive big-

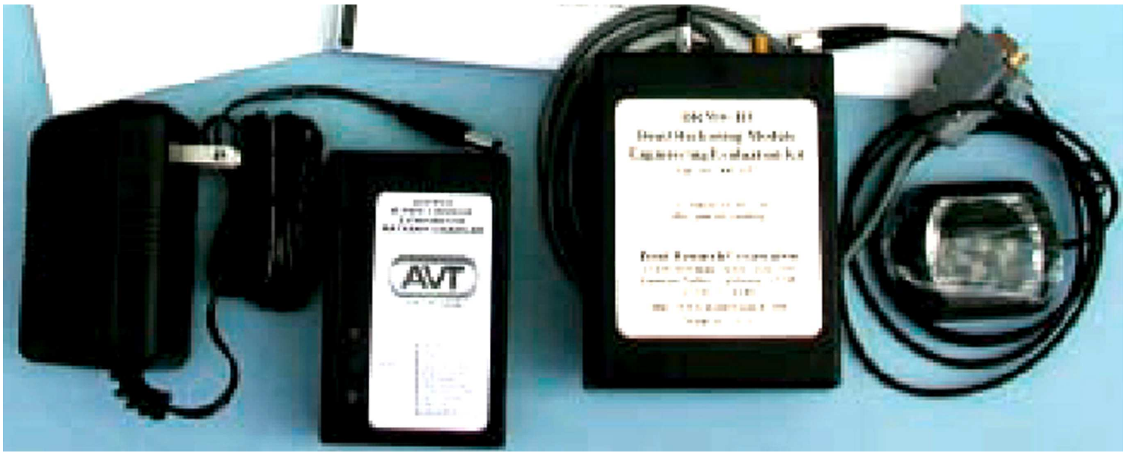


Figure 3.20: Dead Reckoning Module. (Photograph used with permission, courtesy of Robert W. Levi (President, Point Research Corporation).)

screen viewing experience (virtually 45 inches at 2 meters). More importantly, the Cy-Visor is small, lightweight and fits snugly to the head ensuring comfort over extended hours of use therefore making it an ideal candidate as the output device for wearable computer.

3.2.3 Power Consumption of System

Design of computer systems inherently involves trade-offs between constraints. Historically, the major constraints have been performance and cost. With the advent of mobile computing, power consumption becomes a major issue in system design. This is because a large number of wearable computers are used for augmentation purposes, requiring the feature of always on and always available as mentioned. But the current battery technology has yet been able to support that requirement satisfactorily.

Although in the systems, lengthy continuous use is not a necessity, it would be interesting to gauge the power consumption of the wearable computers. The estimation of power consumption is done component-wise as shown in Table 3.1.

It is noted that both HMD and DRM have their own batteries; in other words, the power used is not drawn from the main battery pad. The main power drain comes from the motherboard. Therefore, for the motherboard with Transmeta Crusoe CPU the power requirement is about 11W. Whereas for the motherboard running Pentium CPU, the required power is about 32W. Since PowerPad 160 supplies 160Wh, it is able to power the Transmeta wearable computer system for about fourteen hours; and the Pentium one for about five hours. As for the Sony battery pack, it provides about 39Wh. Therefore the Transmeta wearable computer system can last about three hours using these batteries; while the Pentium wearable computer can operate for only one hour.

3.2.4 Discussion on Problems Encountered

The technology used in building the wearable computer consisted of three major components: the system unit, a HMD, and the input devices. Existing technologies are used wherever possible in order to minimise cost and time. In the course of development, several technical problems were encountered, and they will be described as follows.

The ease of connecting external components to the motherboard of this non-standard form factor was greatly compromised. For example I need to add in an additional 40-to-44 pin adaptor in order to attached a harddisk to the motherboard. Furthermore, when I tried to enhance the wearable computer's graphic processing power by adding a graphic card, I have failed to make it work. The PC104+ slot on the motherboard needed a PC104+ to PC104 converter as a bridge between the conventional PC104 graphic card and the motherboard. However because of synchronization problems which were caused by the lack of standard in intrinsic

Table 3.1: Power Consumptions of Components of Wearable Computers.

Component	**Details**	**Power Requirement**
1. Transmeta Motherboard	Tiny886ULP from Advanced Micro Peripherals Ltd	around 9W
2. Pentium Motherboard	786LCD/3.5” SBC from Inside Technology	25-30W
3. Firewire Camera	Firefly from Point Grey Research	1.25W active; 625mW on standby
4. Head Mounted Display	Cy-Visor (DH-4400VP) from Daeyang E& C	6W
5. Inertia Sensor	InertiaCube2 from InterSense, Inc.	600mW
6. Bluetooth Device	Bluetooth Developer’s Kit from TDK Systems	2.5mW maximum; 1mW in normal operation
7. Wireless LAN card	DWL-120 Wireless 2.4GHz (802.11b) USB Adapter from D-Link	79mW
8. Dead Reckoning Module	DRM from Point Research Corporation	Average 200mW

hardware design, the graphic card could not function properly. The same problem was confronted when I tried to add a sound card to the system.

Failure to synchronize had also rendered MicroOptical HMD unusable in DSTAR wearable computer. Although it is not necessary to use MicroOptical HMD for the applications developed, this problem had limited the expansion of DSTAR for other operations involving the use of optical see-through HMD.

The communication between the GPS and the InertiaCube sensors was done via the serial ports. Customary communication software had to be made to facilitate this. Unlike the case of a USB port, serial port did not supply power to the devices attached to it. Thus I have to regulate power from the main battery pack for the two sensors. It was noted that InertiaCube was very sensitive to voltage fluctuations. It would malfunction if the voltage changed too rapidly or drastically.

The packaging and arrangement of the power source posted several challenges as well. The Sony InfoLithium batteries came with non-standard connectors. Care must be taken to make sure that the connections were tight and secure when self-made connectors were used. It would prevent unexpected disruption of service or reboot of system.

Another critical problem in wearable computer application is the interference in Wireless LAN communication. This was especially important in outdoor gaming applications because of the high proliferation of Wireless LAN in urban area. Care must be taken to avoid the use of the same bandwidth for proper functioning of the systems.

In summary, the problems faced in developing wearable computer prototypes were mainly due to the lack of standards and support from the industry. Nevertheless, they could be solved when the wearable computer systems are brought to mass-manufacture.

3.2.5 Limitations of Wearable Computer Systems

The main issues on the way to a wearable computer that is acceptable by mass market are:

- adequate miniaturized input devices,
- unobtrusive, see through head mounted displays with high resolution and low power consumption,
- a user interface that is adequate for augmented reality wearable applications,

- compact, low power computer systems capable of dealing with the high signal processing and graphics load encountered in wearable computing,
- miniaturized sensors, and
- a cableless network technology for the interconnection of the wearable components distributed over the users body (personal area network).

The solution to the above problems poses engineering and scientific challenges in five broad areas are: (1) the miniaturization of complex electro-opto-mechanical systems, (2) high performance electronic devices and packaging, (3) computer architecture, (4) object tracking and image recognition, and (5) human computer interfaces. All of the above areas are rapidly advancing open possibilities for improvements in wearable technology.

A particularly rapid advancement is currently taking place in the miniaturization of electro-opto-mechanical system. Recently silicon surface micromachining technologies were developed that allow such systems to be fabricated in VLSI technology compatible with electronic circuits [63, 64]. The technology is referred to as MEMS (for micro-electro-mechanical systems) or MOEMS (micro-opto-mechanical systems) for systems containing optical components. The progress brought about by the MEMS/MOEMS technology is comparable with the transition form discreet transistor based electronics to VLSI circuits. In fact, in the inertia sensor described (InertiaCube2), MEMS technology is applied to reduce the size of the device.

Computer components together with various electronic devices required for common wearable computer applications pose serious difficulties in architectural design and packaging. Weight, size, and ergonomy of the devices made by current manufacturing technology are not up to the ideal requirement of wearable computer systems. Commercial and research systems alike, the head mounted displays are often too difficult to view or too heavy to wear comfortably for extended period of time; input devices are difficult to use or required much learning effort to master; and almost definitely too expensive in price.

Tracking using either sensor or visual is far from perfect. According to You [65], the key technological challenge to creating an augmented reality (which is commonly used as an interface in wearable computer applications) lies in maintaining accurate registration between real and computer-generated objects; i.e. as augmented reality users move their viewpoints, the graphic virtual elements must remain aligned with the observed positions and orientations of real objects. This is difficult because of the inaccuracy in tracking and the sensitivity of human visual perception to misalignment. Nevertheless, with consistent improvement in sensors technology and computing power, this matter is in hope of solution in the near future.

Chapter 4

Wearable Computer Applications: Game City and Interactive Theater

This thesis proceeds to present applications developed based on the wearable computer constructed as described in the previous chapter. The first is an entertainment system called “Game City” which is an embodied (ubiquitous, tangible, and social) wearable computing based augmented reality (AR) game space which regains the social aspects of traditional game plays whilst also maintaining the exciting fantasy features of classical computer entertainment. The second application is named “Interactive Theater” which is essentially an interactive theater based on an embodied augmented reality space and wearable computers.

“Game City” ventures to provide the full spectrum of game interaction experience ranging from the real large-area physical, to 2D and 3D augmented reality, to the virtual environment. The virtual world is tightly coupled with the physical world as co-located players in the virtual world must also be co-located in the physical world. Furthermore, the wearable computer system allows communication and status updates between all environments and realities. It can seamlessly transfer between multiple interfaces, ranging from simple text, to 2D graphics, to fully immersive 3D virtual reality. Using real-time sensing of the environment, the wearable computer system captures human physical interaction with the real-world environment as essential elements of the gameplay. The system also allows tangible interactions between players and virtual objects, and collaborations between players in different levels of reality. Thus, the system re-invigorates wearable computer interaction and entertainment systems with social human-to-human and human-to-physical interactions.

On the other hand, "Interactive Theater" couples embodied computing augmented reality spaces integrate ubiquitous computing, tangible interaction and social computing (these technical terms will be described in the following paragraphs) within a augmented reality space. This space enables intuitive interaction with physical world and virtual world in the arena of artistic expression. I believe this system has the advantages of supporting a new form of interactive theater experiences featuring augmented reality space, and interactive live 3D characters.

4.1 Game City: A Ubiquitous Large Area Multi-Interface Augmented Reality Game Space for Wearable Computers

4.1.1 Introduction

"Game City" is a novel wearable computer interaction and entertainment system which provides an interactive physical and augmented reality computer environment that spans large areas, allows multi-users, and can be extended to a whole city. Using wearable computers and augmented reality, I overlay the physical world with a virtual environment to allow a large-scale social interaction in the real world. The research philosophy for developing such wearable computer systems is that humans, as social creatures find physical interaction, touch, and human-to-human presence essential for the enjoyment of life [66]. However present computer entertainment focuses the user's attention mainly on computer screens or 2D/3D virtual environments. Therefore physical and social interaction is constrained, and natural interactions such as gestures, body language and movement, gaze, and physical awareness are lost [51]. In the pre-computer age, games were designed and played out in the physical world that we live in. Games are also often played by groups of people, with the purpose of making use of our social interaction abilities [67]. We feel entertained in these kinds of games by applying our skills of physical and social interaction in a special manner according to the game rules.

Computer technologies have opened a new direction for game design and gameplay. In 1961, MIT student Steve Russell created Spacewar, which can be considered as the first interactive computer game, on a Digital PDP-1 mainframe computer [68]. In that game, two spaceships pit against each other with limited fuel supplies in a missile duel. These spaceships are rendered in rough outlined vector graphics. Decades later, the method for interacting with computer games has not changed much. Almost all computer games limit the players in front of a 2D screen. Thus, it becomes an abstractive and indirect obstacle between the player and the game context. In addition, players have very little physical body movement, comparing to playing a pre-computer type game. Furthermore, with the support of Internet, we no longer need to be in physical proximity for game playing. Interaction with other users on is screen character or icon. Paradoxically, it has created a barrier between humans, because humans have a psychologically need for social and physical interaction [69]. Therefore we can see that interactions in pre-computer games consisted of two elements: human to physical world interaction and human-to-human interaction. In a computer game, the former is lost and is replaced by an indirect human to virtual world interaction, and the latter has been changed to an unnatural indirect and non-tangible mediated manner. With these inadequacies, it is a compelling research task to find an approach to retain the exciting elements brought by computer games, as well as simultaneously regaining the natural physical world interactions embedded in pre-computer games. Hence, in this research a novel approach is developed that employs the theory of embodied computing together with wearable computers and augmented reality to create a novel computer game space.

Embodied computing [70] is a next generation computing paradigm which involves the elements of ubiquitous computing [71], tangible computing [72], as well as social computing [73]. The concepts of ubiquitous and tangible computing propose that the computer is embedded in our environment, in objects, and in the background. Similarly social computing proposes that the real-time and real-space activities of humans as social beings are placed at primary importance.

In the system of "Game City", games are situated and carried out in the physical world. Players can walk around a theoretically limitless area such as a whole city and find, and pick up real objects to physically interact with the game space. What enhances the physical space is that the real object and real environment may be augmented with virtual objects or virtual figures. Thus, the benefits and excitement of computer entertainment is also incorporated into the physical space. In our system co-located players in the virtual world must also be co-located in the physical world. Thus there is a synergy between the physical and the virtual environments. Thus, players will experience a novel full spectrum game experience ranging from physical reality, augmented reality, to virtual reality, and in a seamless way featured with tangible interfaces and social interaction.

Thus, the aims and contributions of the wearable computer game system can be summarized as follows:

- Synergy between physical and virtual world: (a) To tightly couple the virtual world with the physical world where co-located players in the virtual world are also be co-located in the physical world. (b) To create an overlay of a virtual world into the real world in order to facilitate social interaction in the real world.

- Physical and social interaction: (a) To create a game that is played in the physical world, with the user able to freely move about the world in a very large-scale area. (b) To allow simultaneous participants playing together in a shared environment, while maintaining the social, non-mediated interaction between players. (c) To ensure players are able to use physical cues like gestures, tangible interaction, body language, and gaze to communicate. (d) To recognize the physical co-location of players and objects in the world as essential elements of the game.

- Wearable and ubiquitous computing: (a) To directly supports mobile wearable computer collaborative systems, with sensors and displays, and thus to enable a personal ubiquitous computing experience. (b) To allow distributed and tangible interaction aspects that supports the execution of the game. (c) The wearable computer system allows communication and status updates between all environments and realities, and can seamlessly transfer between multiple interfaces, ranging from simple text, to 2D graphics, to tangible augmented reality, to fully immersive 3D virtual reality.

4.1.2 Game City Interface

In this system, as pictured in Fig. 4.1, the game is situated and carried out in the physical world with a large space which can span city-wide areas, and allows human to human and human to physical touch interaction. Each person carries a wearable computer (this hardware/software system will be detailed in the following sections). "Game City" comprises of three stages, in all of which two players should collaboratively finish some outdoor wide-area tasks, and then rescue a princess in a castle controlled by a witch in a virtual world.

In this game space, a princess is captured by a witch and is locked in the witch's castle that is located in a mysterious land. To play the game firstly the two players need to find two map pieces of the mysterious land and other necessary treasures (such as magic wands, keys, etc.). Secondly, they should fly above the land and look for the castle, after that, they need to fight and defeat the witch. Finally, they enter the castle to find the princess, and thus they complete the game mission. Thus, the game consists of three main game stages which are detailed below:

Figure 4.1: Game-City Concept.

Stage 1: Physical Land (City-Wide Area) Exploration Stage

This is an augmented reality experience stage, which allows the users to experience tangible interaction and physical world contextual awareness and social interaction. In this stage, players need to collect enough treasures and clues, and avoid dangers in the city-wide physical game area (however this test system was actually implemented in a smaller Clementi suburb area of Singapore). Thus, this game is played in the outdoor physical world, and each player has great mobility to freely move about the world. Using the wearable computer and real-time sensor tracking I create an overlay virtual world to facilitate social interaction in the outdoor physical world. The wearable computer provides interaction through sensors that include GPS position, magnetic field data, inertia and orientation, and wireless LAN communications. This is outlined in Fig. 4.2 and will be fully detailed in the following paragraphs.

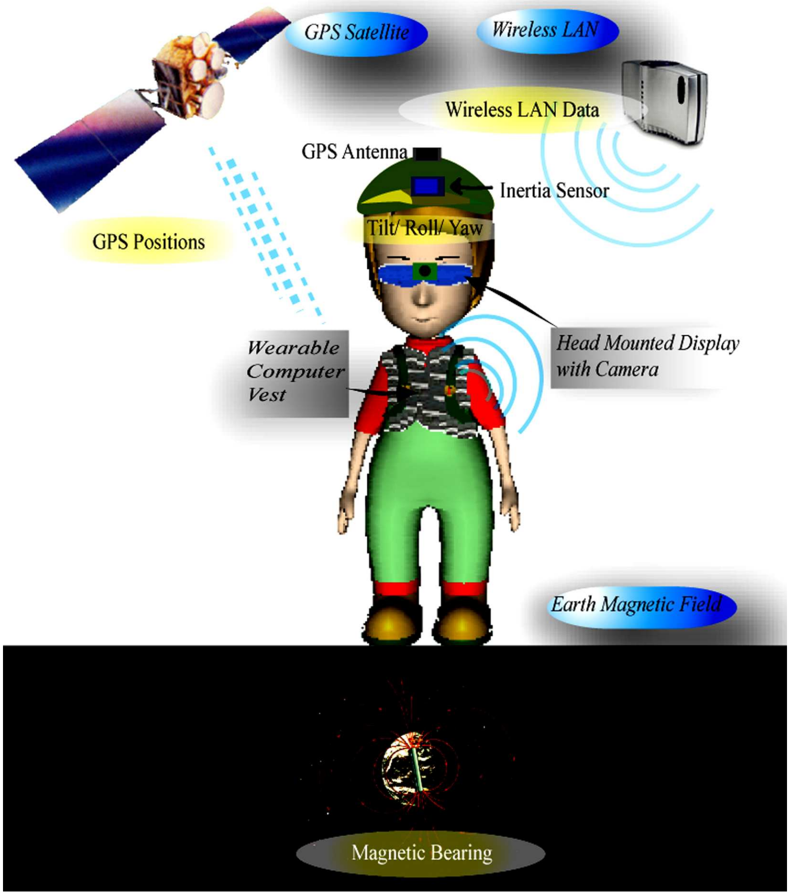


Figure 4.2: Wearable Computer Sensor System for Outdoor Augmented Reality.

The interaction in this stage of the game can be summarized as follows: The players must physically move around their real world to find clues and treasures. Furthermore, players are required to be in the vicinity of one another to exchange information and hints. They are encouraged to engage in face-to-face interaction, i.e. they talk and gesture directly to one another. There are four players in the game; namely two pacmen and two ghosts. There are also two remote players over the Internet who act as helpers.

The virtual world is overlaid in the physical world with augmented reality information see through the first person perspective through a HMD (as shown in Fig. 4.3). Using real-time tracking of the players' location in the physical world, as well as their head orientations, I provide text labelling of important landmarks in the physical world, as well as information such as real-time location on a 2D map, real-time compass orientation, and the name, position, and direction of nearby players (within a 100 meter radius). Mission statements and clues are given through the augmented display. For example if a magic key must be found, an arrow will guide the user to the general location (refer to Fig. 4.3).

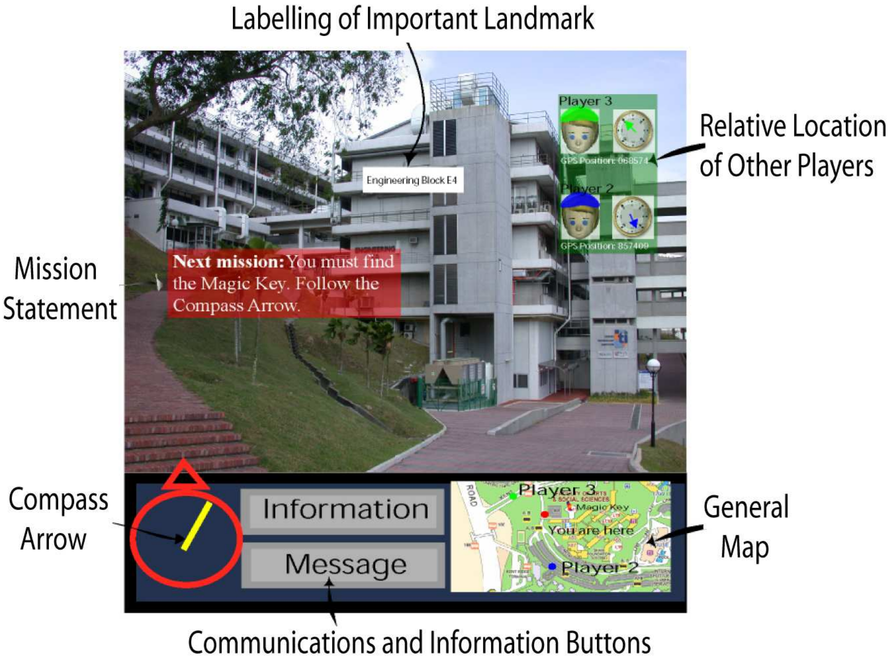

Next mission: You must find the Magic Key. Follow the Compass Arrow.

Figure 4.3: Wearable Computer Outdoor Augmented Reality Interface.

However, due to the fact that the GPS system has a low accuracy of approximately 10 m, I use this to advantage. When the user is near an area where an object is to be found, she must then still search and find a physical marker or box, because the exact location cannot be determined from the sensors. I also place some boxes inside indoor areas such as a train station lobby. This means that the GPS sensor will become inoperative and the user must find himself the box in the indoor area. This adds a physical hide-and-seek element to the game, as well as encouraging the users to talk to each other to exchange hints and tips, in a human-to-human social manner. In the secret locations which the players must find, are hidden some boxes or markers, which contain virtual objects that represent treasures (for example a map piece) or dangerous objects (for example bombs). The players will see these virtual objects shown in the box as if they are real 3D objects. Physical movement and tangible interaction is essential, as the players must physically walk around in the physical space to find, and physically pick up and open the boxes. The players will obtain scores if they find a treasure, and will lose scores if they find a dangerous object. When the players obtain all necessary treasures and enough scores, they finish stage one and thus start the next stage. The example of a box being open is shown in Fig. 4.4, here an air-plane is found which will be used by the user in the next stage of the game. In this mode, the wearable computer implements the augmented reality interaction using the camera as input sensor (i.e. it becomes the primary sensor).

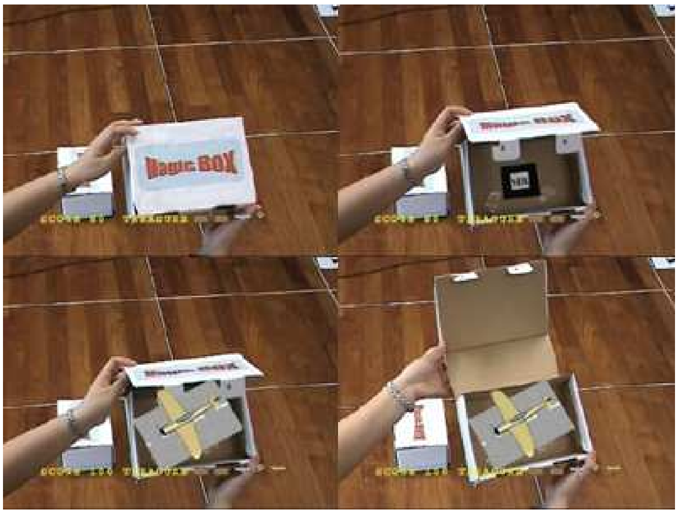


Figure 4.4: Tangible Interaction: Opening a Real Box to Find Virtual Treasures Inside.

Stage 2: Virtual Land Exploration Stage

Once the players have completed the first stage, they will be guided to a “secret” location via directional text messages. The “secret” location contains a high resolution 3D AR and VR game system which is termed “TouchSpace” to emphasize that it focuses again on the physical interaction of the players. The virtual world in this stage is tightly coupled with the physical world. In order to enter the virtual world of the TouchSpace system, the players must physically find the game area and enter the system physically together. Thus, the co-located players in the virtual world must also be co-located in the physical world. Hence, there is a synergy between the physical and the virtual environments.

The system uses IS900 [74] inertial-acoustic hybrid tracking devices that are mounted on the ceiling. While players walk around in the game space, their head and hand position are tracked by the tracking devices. I use the user’s location information to interact with the system, so that the user can actually interact with the game context using their bodily movement in a room-size area, which incorporates the social context into the game experience. A very important aspect to note is that there is a seamless transition between the TouchSpace system and the user's wearable computer. The TouchSpace system automatically communicates to the wearable computer through wireless LAN whenever a wearable computer is detected. This is outlined in Fig. 4.5 and Fig. 4.6. Then there is seamless transition of information about the player and her status on entry (for example does she have the map, what magic potions she possesses). After exploring the TouchSpace world there is also a seamless transfer of information to the wearable computer. For example if the user has found an object in the TouchSpace environment, it will be updated in the wearable computer. This also provides a very tightly coupling of the virtual world with the physical world. For example to operate a virtual magic potion found at the physical train station (as described earlier) the user must first find the magic wand inside the TouchSpace virtual environment.

The communication between the wearable computer and the TouchSpace system is established based on wireless LAN. Fig. 4.7 demonstrates the communication protocol. When a player finds a TouchSpace zone, and wants to join the AR/VR augmented reality (AR) game provided by this hotspot TouchSpace system, her wearable computer will send an entering-request packet to the TouchSpace system. If the TouchSpace system can support one more player, it will send back an entering-approve packet to the wearable computer, and allocate a "local AR game user id" to the player. Then the wearable computer will send the user status information to the TouchSpace system. The latter will carry on to provide the AR game to the player, according to the status information. After the player has finished the game task in this hotspot, he/she may wish to leave and go to another hotspot. At this time, the leaving-request packet will be sent to the TouchSpace system from the wearable computer. The TouchSpace system will send back a status-update

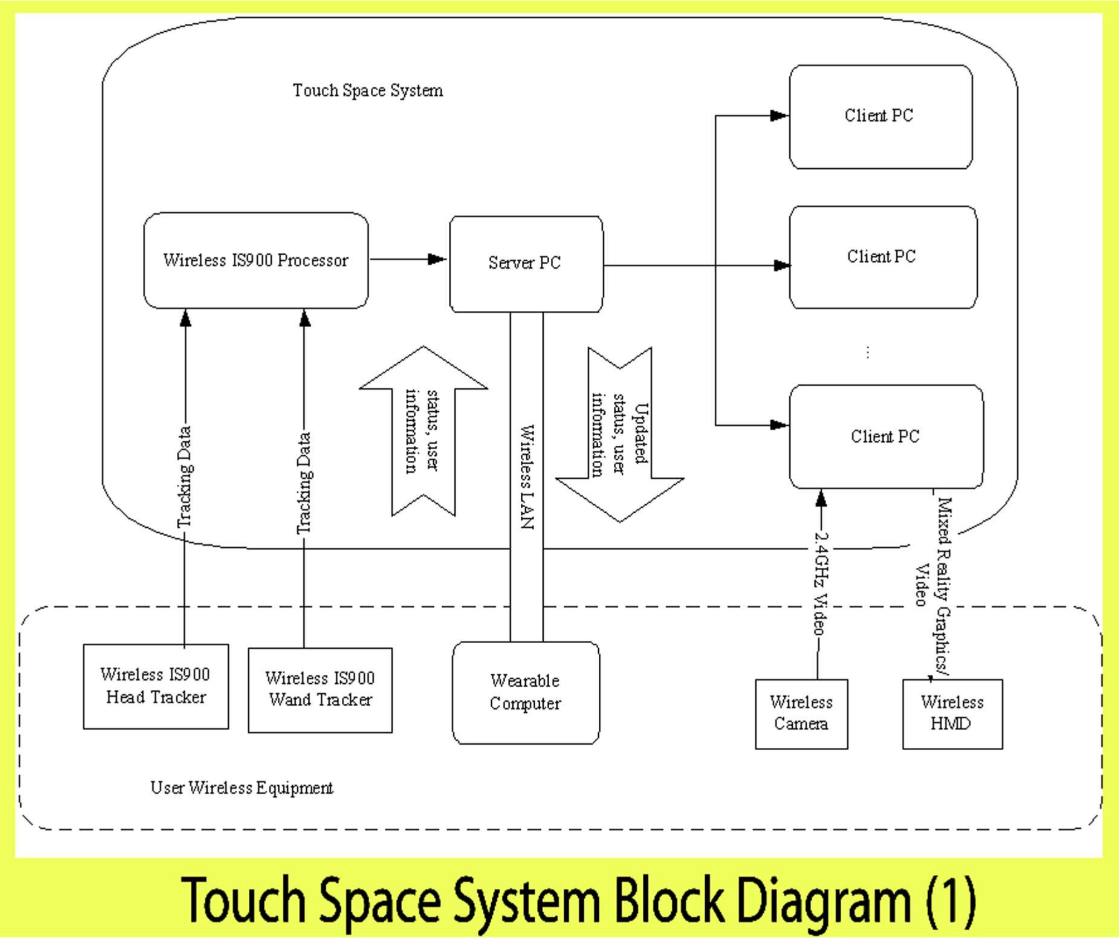


Figure 4.5: TouchSpace Communication System Part (1).

packet to update the status information of the player to the wearable computer. And the TouchSpace system will also send a leaving-approve packet to the wearable computer to acknowledge the player's signing out from the zone.

Stage 2 is an augmented reality (AR) experience stage, which stresses the seamless interaction with virtual objects and virtual figures with body movement, and the seamless transitions between AR world and the VR world. The two players need to find the castle in the virtual land. They will hold a small virtual 3D window through which they can see part of a virtual land which appears on the ground. Since they can only see the part of the virtual land corresponding to their current

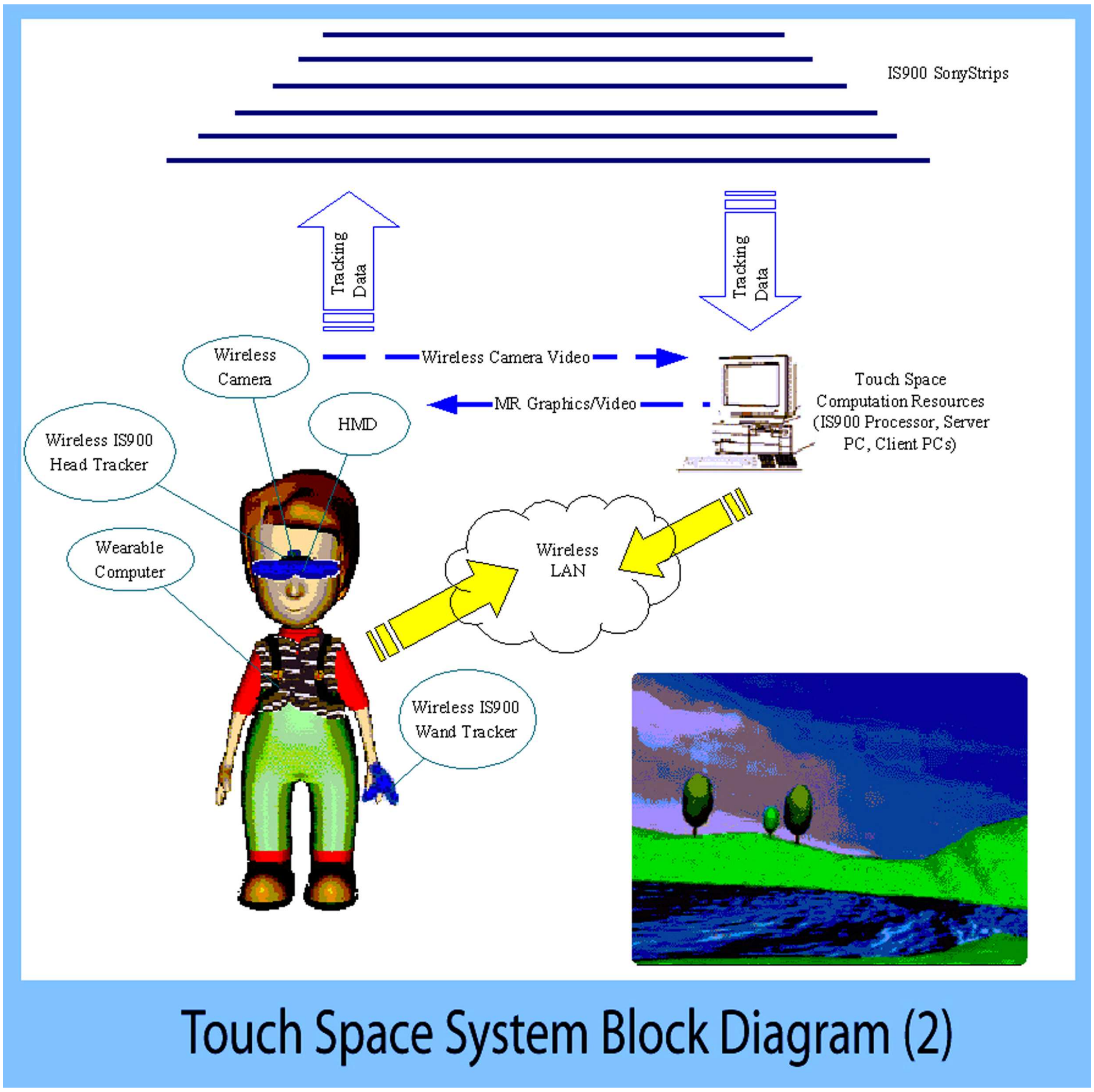


Figure 4.6: TouchSpace Communication System Part (2).

physical body location, they need to walk their body around in the room-size area to be able to find the castle, thus increasing body movement and interaction. Furthermore, each player views a virtual 3D airplane flying above their wand. Tangible interaction (the virtual plane is directly tied to the player's wand), ubiquitous computing (the virtual land is embedded in the physical space), and social computing (the players explore the area together, and see each others body movements and

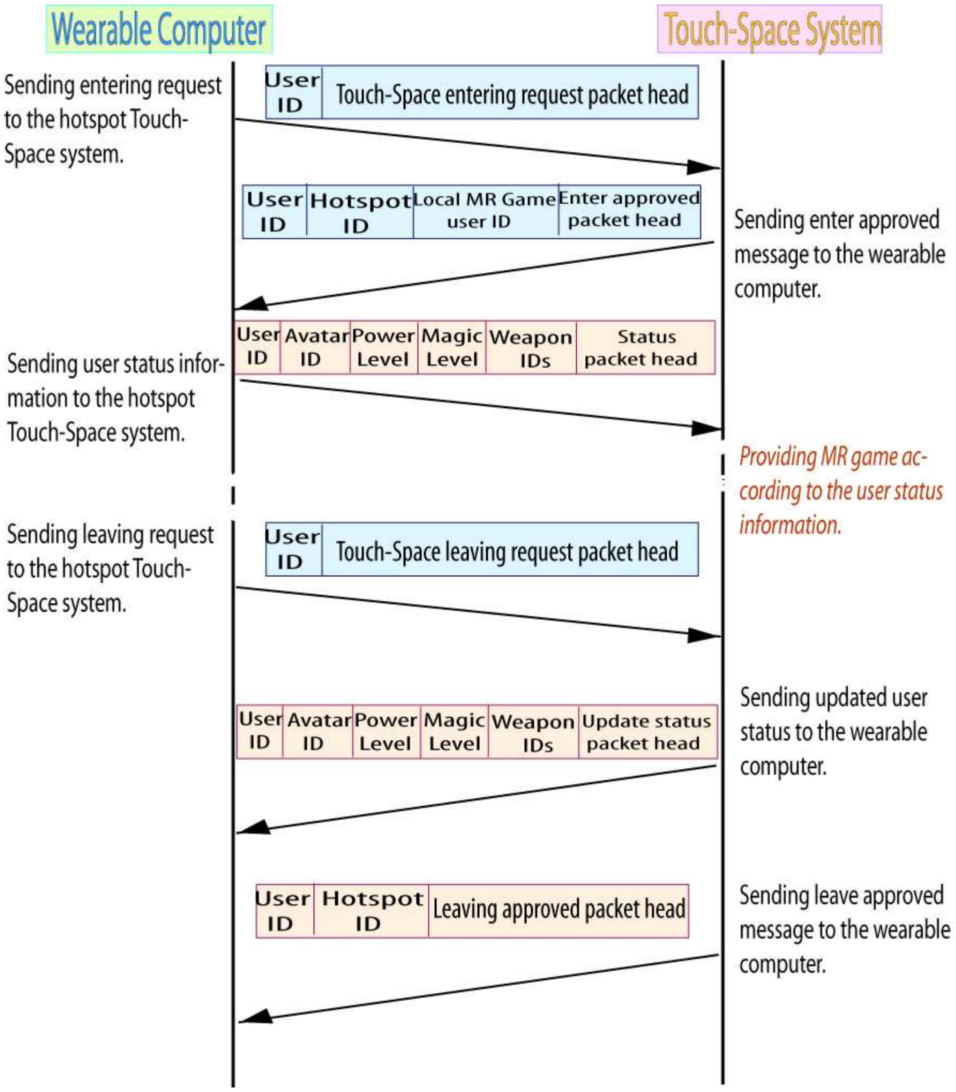


Figure 4.7: Communication between Wearable Computer and TouchSpace System.

gestures) are exemplified. It is noted that in this system, the virtual 3D world is directly and accurately tied to the actual physical location of the wand. Thus, this directly ties the physical world to the virtual world in a ubiquitous manner, and the players view the world by moving their physical hands holding the wands in a tangible manner.

The three pictures in Fig. 4.8 shows the scrolling 3D landscape when the player is looking for the castle. A small virtual plane is attached to the wand as an avatar for the user, as if the user is exploring the game space by manipulating the plane. Once the players find the castle, they will see the witch flying out of the castle and the small magic window which they hold, and the witch will "jump" into the physical environment where they are located. The witch will fly above the players and throw fireballs to the players. The players need to physically move their body to avoid being hit by the fireballs and at the same time use their virtual gun fire to shoot at the witch as shown in Fig. 4.9. When they defeat the witch, by flying into the 3D window, they will experience a seamless transition from the AR world into the VR world and start the next stage. This is a VR experience stage, featured with fully immersive VR navigation. In this stage, the players will see they are in the virtual castle and they need to navigate in it trying to find the princess. In this case the players can see each other as avatars in the VR environment. A very interesting feature of this stage is that if one player has entered the VR environment, whilst the other is still in the AR environment (stage 2), the VR player will see the players hand movements represented by an airplane in the sky tied to the AR players hand movements. Furthermore, the AR mode player will see the VR mode player as a small avatar moving around in her 3D window.

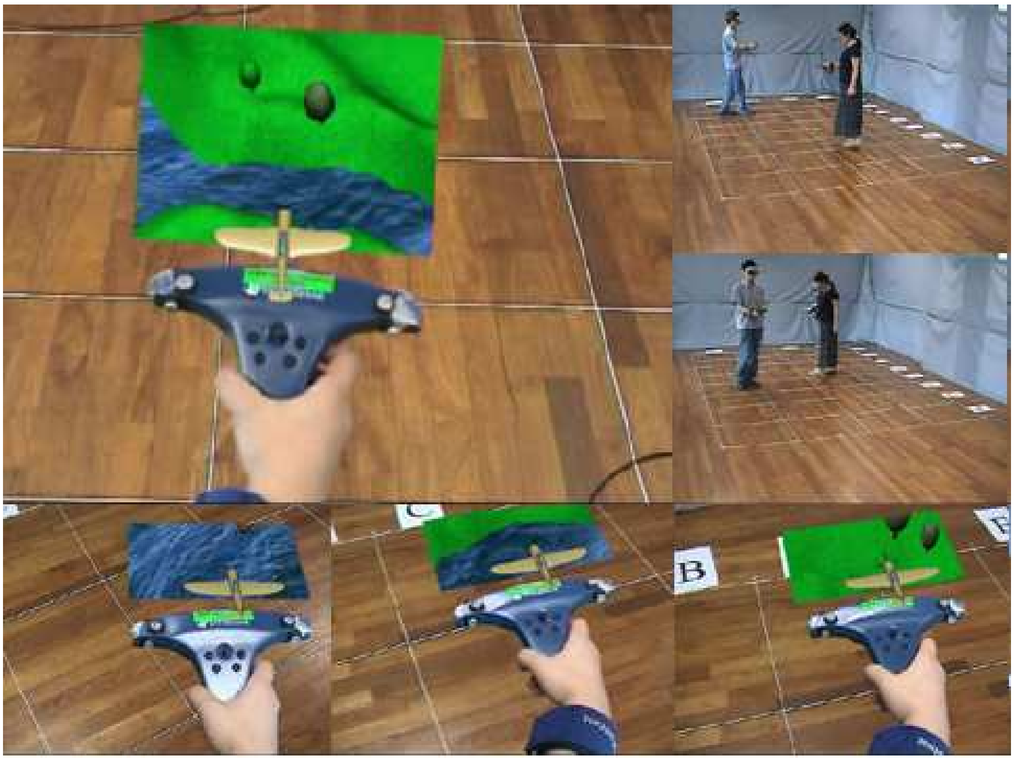


Figure 4.8: Looking for the Castle through a “Magic 3D Window”.

Figure 4.9: Collaboratively Fighting the Witch.

Stage 3: Virtual Castle Exploration Stage

Finally in the fully immersive VR mode (as seen in Fig. 4.10), the wand can be used as a navigation tool. Players use the joystick on the wand to navigate in VR world. The virtual character's location will move according to the player's navigation control and the virtual character's head will move according to the player's viewpoint. This way, players can be aware of where each other are looking. With support of above technologies and interfaces, the players can actually experience a full spectrum of embodied interaction with the new augmented reality game space. This demonstrates a natural and seamless interaction between the physical and virtual world, and re-invigorates computer entertainment systems with human-to-human and human-to-physical social interactions.

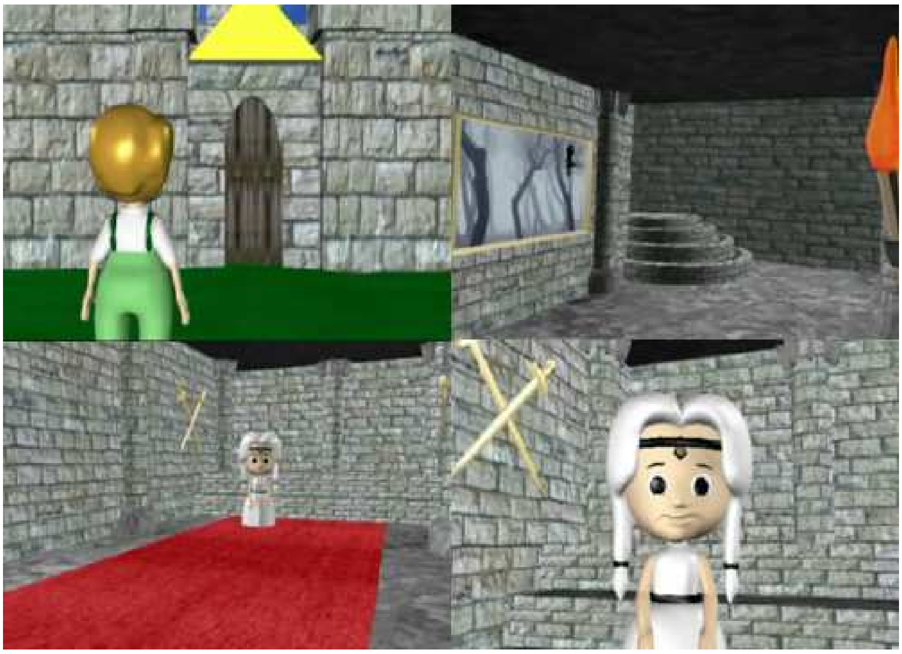


Figure 4.10: Navigation in VR mode.

4.2 Interactive Theater

4.2.1 Introduction

Digital technology has given rise to new media forms. Interactive theater is such a new type of media that introduces new digital interaction methods into theaters. In a typical experience of interactive theaters, people enter cyberspace and enjoy the development of a story in a non-linear manner by interacting with the characters in the story. Therefore, in contrast to conventional theater which presents predetermined scenes and story settings unilaterally, interactive theater makes it possible for the viewer to actually take part in the plays and enjoy a first-person experience.

For this project, I am concerned with embodied mixed reality techniques using video-seethrough HMDs (head mounted display). The research goal is to explore the potential of embodied mixed reality space as an interactive theater experience medium. What makes the system advantageous is that embodied mixed reality and wearable computers with live 3D human actor captured is combined for an increased sense of presence and interaction. An embodied mixed reality space is the assimilation of embodied computing and augmented reality techniques. Mixed reality (MR) covers the full reality-virtuality spectrum proposed in [75], involving the spectrum of physical reality, augmented reality and virtual reality. Embodied computing [70] is a next generation computing paradigm which involves the elements of ubiquitous computing [71], tangible computing [72], and social computing [73] as mentioned before. It places computation and interaction throughout and with the environment, as well as incorporating the sociological organization of interactive behavior. Ubiquitous computing provides advantages for creating a novel theater space as it provides technology that is designed to be embedded in the natural human environment which responds to people's needs and actions in a contextual manner [76]. Tangible computing directly links the digital world and the physical world and allows the computational world to engage and employ our physical and tactile skills which we are intimately familiar with. It also provides a seamless method of allowing natural physical interaction and collaboration between people. Social computing allows advantages for the novel interactive theater space by incorporating the integration of people's interaction with technology that does not follow formal theoretical abstracts or procedures, but are improvised naturally in real-time. Combining mixed reality with embodied computing allows us to create a rich physical environment, where digital 3D objects and characters are embedded and are manipulated directly in a collaborative manner with natural interactions in the physical world. Therefore, it is possible to provide user a novel interactive theater experience, which I will detail in the following sections.

Significant research work has been conducted for interactive theater in virtual reality community [77, 78, 79], but little work has been done with mixed reality. One of the pioneers in this area MacIntyre [80] has conducted research to explore augmented reality as an entertainment and interactive theater medium. However, they used 2D video avatars as virtual characters to interact with users. The novel contribution of "Interactive Theater" system is that I, together with colleagues in the lab, have developed a ubiquitous outdoor wearable augmented reality system that seamlessly integrates with an embodied mixed reality theater and the enhanced presence of virtual 3D live human actor. In the interactive theater, the user will firstly interact in an outdoor wearable computing augmented reality space, in which the wearable computer serves as a guidance for many theater stages in a campus-size area. On the user's wearable display, she can obtain information of what stages are currently set up in the area, and can be led to the various stages by following the instructions displayed in the AR interface. By this way, a multiple-act story can be set up in the physical area so that more realistic mood can be set to allow the user feeling more involved in the theater. For example, in Shakespeare's tragedy Hamlet, I can set up multiple stages in different places, where the user needs to travel physically between these stages according to the story. When user is directed to a stage following the story of the theater, she can then switch to an indoor mixed reality theater space, where he can either play a role as a first-person in the theater and interact with other virtual characters represented as 3D live avatars, or view the theater as a third view person. Furthermore, multiple users can participate the theater simultaneously and aware of each other's existence in the whole story. To summarize, this research work thus has the following main features: (1) providing a novel embodied computing (ubiquitous computing, tangible interaction, social computing), MR (AR, VR) wearable interactive space for interactive theater, (2) implementing 3D live human theater actors in mixed reality.

4.2.2 Background Theory

Interactive theater in embodied mixed reality space is an electrical theater that gives visitors a novel theater experience which extends a traditional theater sensations, with exciting features such as human-to-human social interrelation and physical objects interaction. In this section, the technologies and background theory of mixed reality, embodied computing, and live 3D actors used in this work will be summarized.

Embodied Mixed Reality Space

In order to maintain an electrical theater entertainment in a physical space, the actors and props will be represented by digital objects, which must seamlessly appear in the physical world. This can be achieved using the full mixed reality spectrum of physical reality, augmented reality and virtual reality. Furthermore, to implement human-to-human social interaction and physical interaction as essential features of the interactive theater, the theory of embodied computing is applied in the system. As mentioned before, the three important research paradigms on which embodied computing is founded, are Weiser's ubiquitous computing [71], Ishii's tangible bits or "things that think" [72], and Suchman's sociological reasoning to problems of interaction [73].

Ubiquitous computing deals with computing in the environment and with activities that take place in the context of the environment. Tangible interaction deals with using the physical world and physical object manipulation to interact with the digital world. Both share the view that interaction with computers should exploit our natural familiarity with the physical environment and physical objects. Both tie the computer interaction with physical activities in such a manner that the computer is embedded in the activity. In this way, the environment and physical objects become the computer interface.

The third research paradigm of embodied computing is social computing, or the study of the context in which interaction with computation occurs. The important work of Suchman on this topic draws on ethnomethodology to analyze interaction and social conduct. In ethnomethodology, social conduct is an improvised affair, which is a real-time and non-linear. This perspective argues that it is the context in which an interaction takes place that allows people to find it meaningful.

Experimental investigations have found that people's interaction with technology does not follow formal theoretical abstracts but are improvised in real-time [70]. Embodied mixed reality space uses the social computing concepts to allow a natural physical and social interaction between users. Furthermore natural interactions such as gestures, body language and movement, gaze, and physical awareness are always visible in the space. The system also supports multiple simultaneous participants in a human-to-human social manner. Furthermore, as will be detailed below, the system even supports a high level of social interaction between different spaces. Through a seamless traversable interface, the visitors can transit to and fro fully immersive virtual environment. However, even when one person is in virtual reality, and the other is in physical reality, both can interact and view each others movements. It should be noted that these three research visions mentioned above have a central strand that deals with the role of context in interaction. The role of context is seen in the spatial and temporal context found in ubiquitous computing, the physical context found in tangible computing, and the social, cultural, organizational, and interactional context found in social computing. Thus, all are mutually dependant on the concept of embodiment, or a presence and interaction in the world in terms of real-time and real-space. Hence, they define the concept of embodied computing [70]. For example ubiquitous and tangible computing is based upon the idea of the computer being embedded in our environment, in objects, and in the background. Thus the interaction is embodied in the physical environment, rather than on abstract representations on a computer system. Similarly social computing places the real-time and real-space activities of humans as social beings, or embodied actions, at primary importance. Embodied computing ties all these ideas together, as a single research vision. Furthermore, embodied computing foresees that the future of human-computer interaction will lie in an interface to computing that appears throughout our physical space and time. Thus, humans as physical beings now actually become situated inside the computational world. Interactive theater in embodied mixed reality space is an exploration of the embodied interaction within a mixed reality collaborative setting. The result of the project is a unique electrical theater which combines the interactions of natural human-to-human, human-to-physical (indoor and outdoor using wearable computer) world and human-to-virtual world, and provides a novel theater experience ranging from physical reality, augmented reality, to virtual reality.

Live 3D Actors

As mentioned above, this research aims to maintain human-to-human interaction such as gestures, body language and movement between users. Thus, I have developed a live 3D interaction system for viewers to view live human actors in the mixed reality environment based on Simon Prince's work [1]. In fact, science fiction has presaged such interaction in computing and communication. In 2001: A Space Odyssey, Dr Floyd calls home using a videophone - an early on-screen appearance of 2D video-conferencing. This technology is now commonplace. More recently, the Star Wars films depicted 3D holographic communication. Using a similar philosophy, computer graphics to create real-time 3D human actors for mixed reality environments. It can be noted that conventional 2D human capture does not allow large user movements and gestures to be captured [81], there are no spatial cues between participants [82], and participants cannot easily make eye contact [83]. Collaborative virtual environments restore spatial cues common in face-to-face conversation [84], but separate the user from the real world. Moreover, non-verbal communication is hard to convey using conventional avatars, resulting in reduced presence [85]. Perhaps closest to the goal of perfect tele-presence is the

Office of the Future work [86], and the Virtual Video Avatar of Ogi [87]. Both use multiple cameras to construct a geometric model of the participant, and then use this model to generate the appropriate view for remote collaborators. Although impressive, these systems only generate a 2.5-D model - one cannot move all the way around the virtual avatar, and occlusion problems may prevent transmission. Moreover, since the output of these systems is presented via a stereoscopic projection screen and CAVE respectively, the display is not portable.

One goal of this work is to enhance the interactive theater by developing a 3D human actor capture mixed reality system (see Fig. 4.11). The part of the work is derived heavily from Simon Prince's work on real time captured content in the form of human beings for mixed reality application [1]. The enabling technology is a novel algorithm for generating arbitrary novel views of a collaborator at video frame rate speeds (30 frames per second (fps)). I render the image of the collaborator from the viewpoint of the user, permitting very natural interaction. In order to integrate the virtual actor seamlessly into the interactive theater environment, I need to generate the appropriate view for each video frame. An attractive approach to fast 3D model construction is shape-from-silhouette. A number of cameras are placed around the subject. Each pixel in each camera is classified as either belonging to the subject (foreground) or the background. The resulting foreground mask is called a "silhouette". Each pixel in each camera collects light over a (very narrow) rectangular-based pyramid in 3D space, where the vertex of the pyramid is at the focal point of the camera and the pyramid extends infinitely away from this. For background pixels, this space can be assumed to be unoccupied. Shape-from-silhouette algorithms work by initially assuming that space is completely occupied, and using each background pixel from each camera to carve away pieces of the space to leave a representation of the foreground object. Clearly, the reconstructed model will improve with the addition of more cameras. However, it can be proven that the resulting depth reconstruction may not capture all aspects of the true shape of the object, even given an infinite number of cameras. The reconstructed shape was termed the "visual hull" by Laurentini [88], who did the initial work in this area. Despite these limitations, shape-from-silhouette has three significant advantages over competing technologies. First, it is more robust than stereovision. Even if background pixels are misclassified as part of the object in one image, other silhouettes are likely to carve away the offending misclassified space. Second, it is significantly faster than either stereo, which requires vast computation to calculate cross-correlation, or laser range scanners, which generally have a slow update rate. Third, the technology is inexpensive relative to methods requiring specialized hardware. For these reasons, the system described in here is based on shape-from-silhouette information. This is the first system that is capable of capturing 3D models and textures at 30 fps and displaying them from an arbitrary viewpoint. It is fully described in [1]. Our system in the lab is related to the work of Matusik [89] who also presented a novel view generation algorithm based on shape-from-silhouette. However, Simon's algorithm is considerably faster. Matusik can generate 320x240 pixel novel views at 15 fps with a four camera system, whereas our system produces 450 x 340 images at 30 fps, based on fifteen cameras. The principal reason for the performance improvement is that Simon's algorithm requires only computation of an image-based depth map from the perspective of the virtual camera, instead of the generating the complete visual hull.

Thus, to provide an enhanced presence in the interactive theater, I superimpose three-dimensional live content into a mixed reality scene. In each frame, the Euclidean transformation between a live 3D actor and the camera/virtual-camera is estimated. The equivalent "virtual view" of the live model is then generated and

Figure 4.11: Live Human Actor Content Rendered from the Appropriate Viewpoint in Real Time.

rendered into the scene at interactive speeds. The three-dimensional structure of the model is calculated using a fast shape-from-silhouette algorithm based on the outputs of fifteen cameras surrounding the subject (as presented in Fig. 4.12). The novel view is generated by projecting rays through each pixel of the desired image and intersecting them with the 3D structure. Pixel color is estimated by taking a weighted sum of the colors of the projections of this three-dimensional point in nearby real camera images. A flowchart summarizing the algorithm is shown in Fig. 4.13. Using this system, I capture live human models and present them via the augmented reality interface at a remote location. The result gives the strong impression that the model is a real three-dimensional part of the scene.

4.2.3 Interactive Theater System

In this section, the details of the Interactive Theater System are introduced. An overall concept diagram of the system to be detailed below can be seen in Fig. 4.14. The system can support three modes of interaction scenarios:

Mode 1: Outdoor Theater Land Exploration

This is a augmented reality experience mode supported by wearable comput-

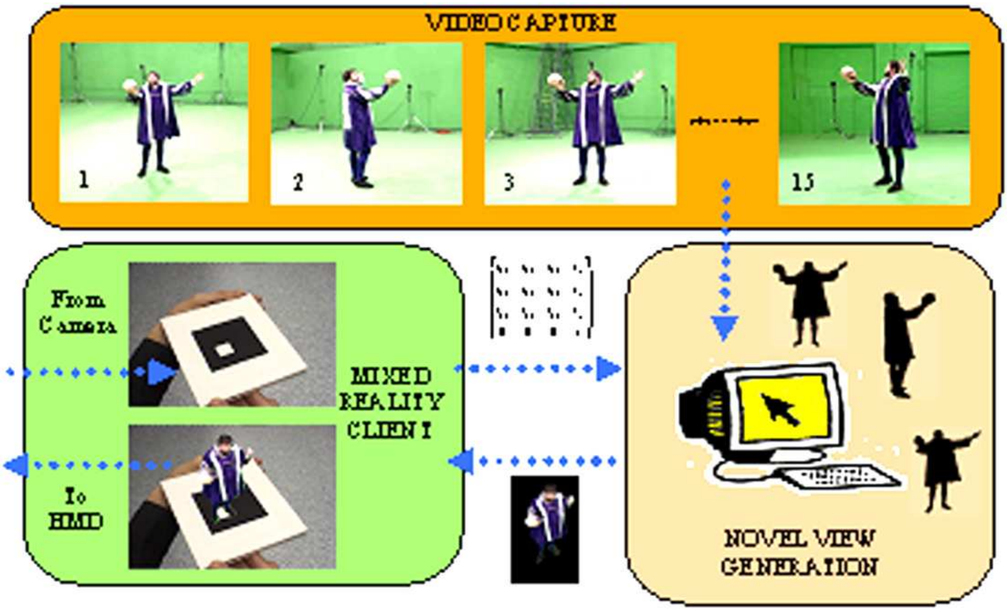


Figure 4.12: Live 3D Viewpoint System.

ers, which allows the users to experience tangible interaction and physical world contextual awareness and social interaction. In this mode, visitors need to walk around an outdoor physical world (for example, some historical sites). They need to collect enough information about the theater before entering it. The aim is to introduce interesting and entertaining interaction in order to make the theater and literature lively and exciting. For example some students studying Shakespeare may currently find it boring. However, with this system, they must walk around the outdoor area and find information and clues about the play and the author of the play, thus adding entertaining outdoor game element to the study. In our concept system the users must walk around the campus and find information on Shakespeare's birth place and information about characters in Shakespeare's plays before being led to the mixed reality theater. Each user has great mobility to freely move about the world. Using the wearable computer and real-time sensor tracking I create an overlay virtual world to facilitate social interaction in the outdoor

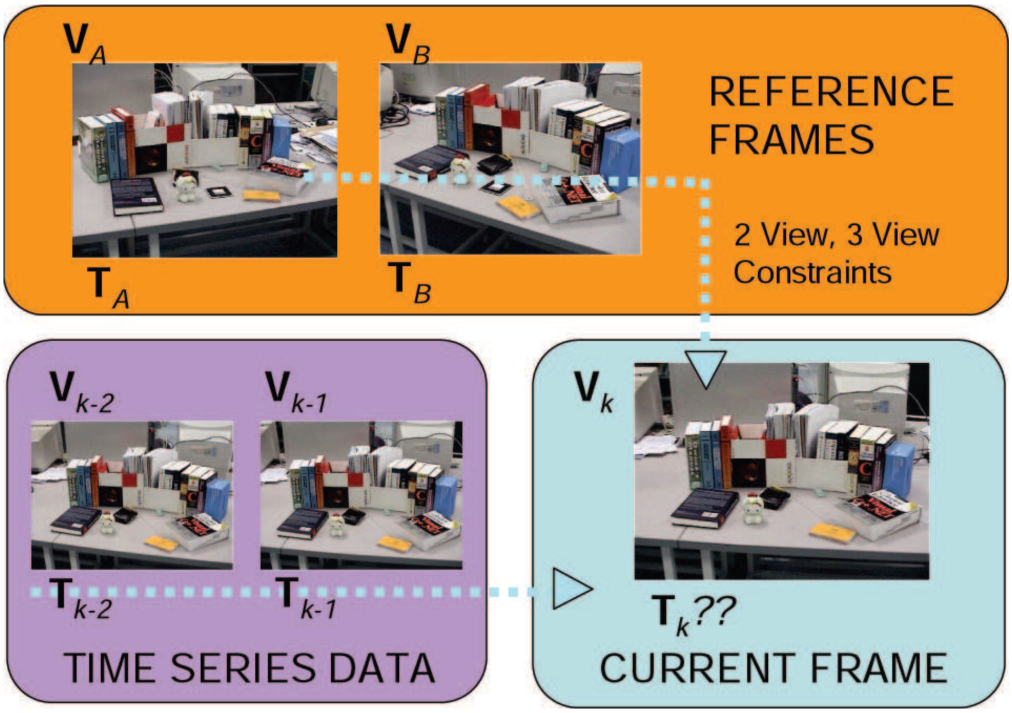


Figure 4.13: The Pose of the Head Mounted Camera is Estimated (Bottom Left), and the Equivalent View of the Subject is Generated (Bottom Right) from the Incoming Video Streams (Top). This is then Rendered into the Image (Bottom Left) and Displayed in the Hmd.

physical world.

The virtual world is overlaid onto the physical world with augmented reality information seen in a first person perspective through a HMD (as seen in Fig. 4.15). In secret locations which the players must find using the wearable computer, are placed with markers. Supported by augmented reality technology, the players will see virtual static humans shown as if they are real 3D objects appearing on the markers. Thus at certain locations various static humans can be associated with the physical location (for example a virtual Romeo can be placed in front of a physical bridge). In our application I simulated this by placing various life sized actors in places around the campus, as can be seen in Fig. 4.16. Note that due to the limitation of the wearable computer, live actors are only shown in the next stage

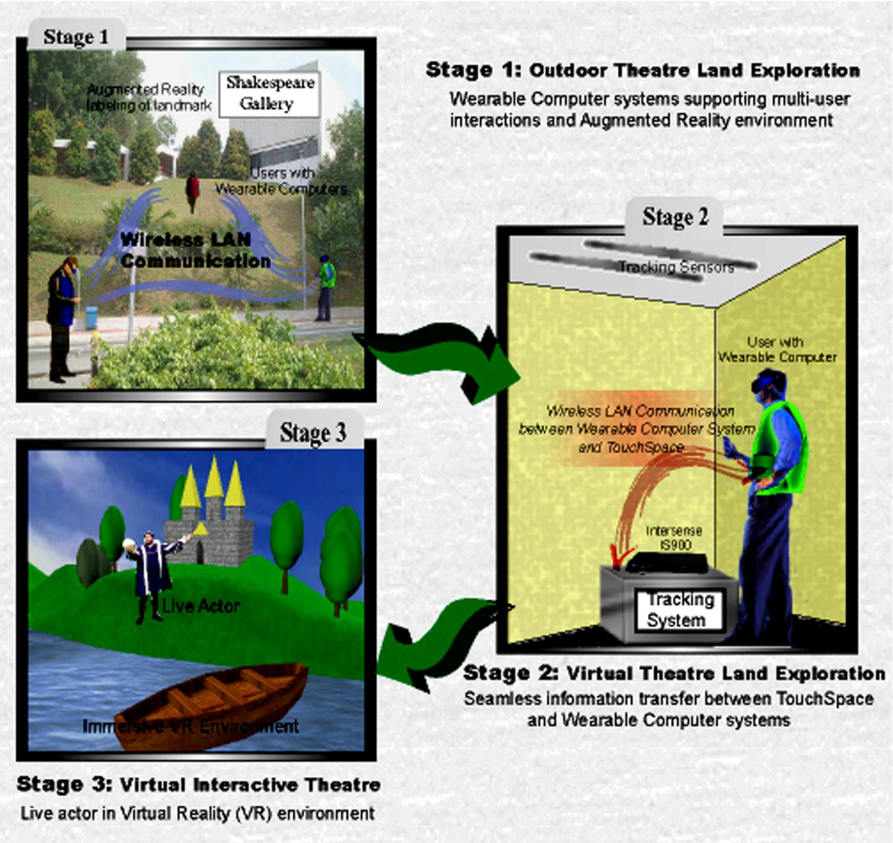


Figure 4.14: Interactive Theater Concept Diagram.

that is detailed below which implements the interactive theater, and this mode can only be seen if the user is wearing the video see-through Sony Glasstron HMD, not the optical see-through type. In this mode, the wearable computer implements the augmented reality interaction using the camera as input sensor.

Mode 2: Augmented Reality Theater Land Exploration

Once the visitors have completed the missions of the mode one, they will be guided to the indoor interactive theaters, which contains a high resolution 3D AR and VR system. These 'hotspot' theater areas uses wireless IS900 (InterSense) inertial-acoustic hybrid tracking devices mounted on the ceiling. While visitors walk around in the room size space, their head and hand position (using wireless tracking devices) are tracked. I use the user's location information to interact with

Figure 4.15: Wearable Computer Outdoor Interface.

Figure 4.16: Virtual Static Actors in Outdoor Locations.

the system, so that the visitors can actually interact with the theater context using their bodily movement in a room-size area, which incorporates the social context into the theater experience.

Mode 2 is an augmented reality (AR) experience mode, which stresses the seamless interaction with virtual objects and virtual figures with body movement, and the seamless transitions between AR world and the VR world. In this mode, a virtual theater land (in our system a simple 3D model of the map of Denmark) is embedded seamlessly to the physical ground in a ubiquitous manner. It is displayed in a virtual windows augmented with the visitors' wands. Through the virtual window, visitors can find the castle where the story of Hamlet Prince of Denmark happened. Thus, this directly ties the physical world to the virtual world in a ubiquitous manner, and the visitors view the world by moving their physical hands holding the wands in a tangible manner. The system hardware and software outline can be seen in Fig. 4.17, where the pseudocode of the computation tasks are also shown.

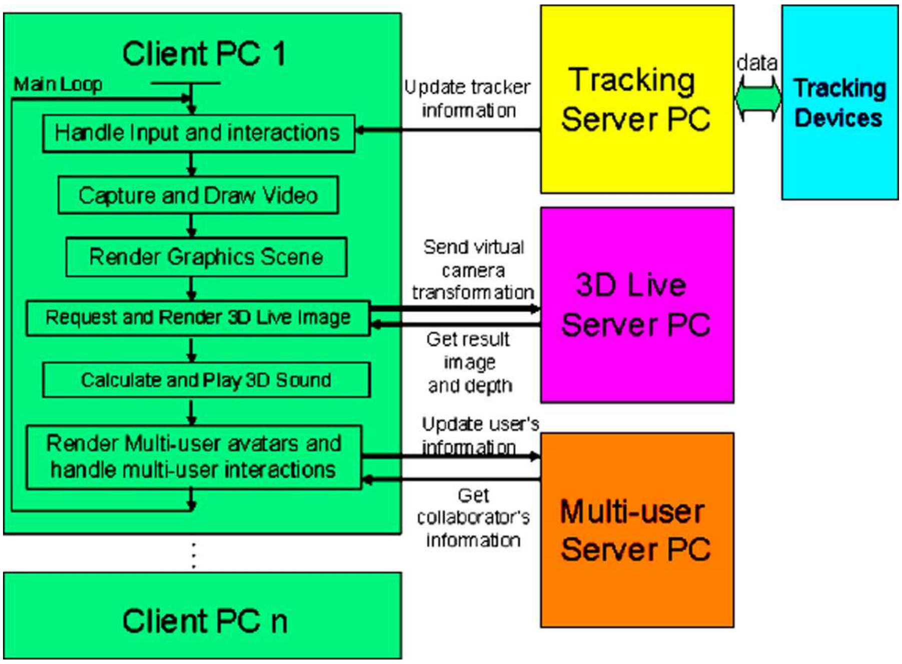


Figure 4.17: Hardware and Software Outline and Pseudo-code of Interactive Theatre Algorithm.

The users can enter the virtual land by teleporting from the augmented reality into the scene. This is achieved by flying into the 3D window, to experience a seamless transition from the AR world into the VR world and start the next mode.

Mode 3: Virtual Interactive Theater

This is a VR experience mode, featured with fully immersive VR navigation. In this mode, the visitors will see they are in the virtual Kingdom of Denmark and they need to navigate to the castle to find the story performed by the 3D live actors. In our simple system, the viewers can see a live 3D captured actor playing Hamlet. As the actor is playing live, there is an enhanced sense of interactivity and presence between the observers and the virtual actor of the theater. In Fig. 4.18 the actual actor is being captured by the virtual viewpoint system, and in Fig. 4.19 the resultant live 3D human in the interactive virtual theater environment. As shown in Fig. 4.19, in this mode the visitors also can see each other as avatars in the VR environment.

Figure 4.18: Capture of Live Actor.

Finally in the fully-immersive VR mode, the wand can be used as a navigation tool. Visitors use the joystick on the wand to navigate in VR world. This way, visitors can aware each other of where they are looking. With support of above technologies and interfaces, the visitors can actually experience a full spectrum of embodied interaction with the new mixed reality theater space. This demonstrates

Figure 4.19: Real Time 3D Live Display of Actor in Interactive Theatre.

a natural and seamless interaction between the physical and virtual world, and re-invigorates computer entertainment systems with human-to-human and human-to-physical social interactions.

Chapter 5

Application: Human Pacman

Human Pacman is an interactive role-playing game that envision to bring the computer gaming experience to a new level of emotional and sensory gratification by setting the real world as a fantasy playground. We have progressed from the old days of 2D arcade Pacman, with incremental development, to the popular 3D game console Pacman, and recently to the online web-based and mobile phone Pacman. With Human Pacman, we have a physical computer fantasy game integrated with human-social and mobile-gaming that emphasizes on collaboration and competition between players. This system is very much a further development from the "Game City" project mentioned in the previous chapter. By setting the game in a wide outdoor area, natural human-physical movements have become an integral part of the game. Pacmen and Ghosts are now human players in the real world experiencing unprecedented level of realism with mixed reality visualization from the wearable computers on them. Virtual cookies and actual physical objects are incorporated into the gameplay to provide novel experiences of seamless transitions between real and virtual worlds and tangible human computer interface. I believe Human Pacman is pioneering a new form of gaming that anchors on physicality, mobility, social interaction, and ubiquitous computing.

5.1 Introduction

In recent years the world has seen the proliferation of highly portable devices, such as personal digital assistants (PDAs), laptops, and cellular telephones. At the same time, trends in computing environment development suggests that users are gradually freed from the constraints of stationary desktop computing with the explosive expansion in mobile computing and networking infrastructure. With this technological progress in mind, Human Pacman is developed to serve as a pioneer in the new genre of computer game that is based on real-world-physical, social, and wide area mobile-interactive entertainment. The novelty of this computer game has the following aspects: Firstly, the players physically and immersively role-play the characters of the Pacmen and Ghost, as if a fantasy computer digital world has merged with the real physical world. Secondly, users can move about freely in the real world over wide area indoor and outdoor spaces whilst maintaining seamless networked social contact with human players in both the real and virtual world. Thirdly, Human Pacman also explores novel tangible aspects of human physical movement and perception, both on the players environment and on the interaction with the digital world. In other words, objects in the real world are embedded and take on a real-time link and meaning with objects in the virtual world. For example to devour the virtual "enemy", the player has to tap on the real physical enemys shoulder; to obtain a virtual "magic" ingredient, the player has to physically pick up a real physical sugar jar with an embedded Bluetooth device attached.

In this system, players are provided with custom-built wearable computers, and they interact both face-to-face with other players when in proximity or indirectly via the Wireless LAN network. Also fully utilizing the high computing power of wearable computers and the underlying network support, Human Pacman takes mobile gaming to a new level of sophistication by incorporating virtual fantasy and imaginative play activity elements that have made computer game popular [90] with the implementation of mixed reality on the Head Mounted Displays (HMD). The players also experience seamless transitions between real and virtual worlds as they swap between immersive first person augmented reality view (with virtual cookies in the real world) and full virtual reality view of the Pac-world throughout the game.

Another important feature of Human Pacman is its inherent support of networked mobile gaming. Mobile gaming is already a big business in Japan and South Korea where up to 70% of users on some networks regularly use the service [91]. According to Forrester Research [92] of the US, within three years 45% of European mobile subscribers will regularly play games on their mobile phones. London-based Ovum [93] forecasts that global spending on mobile games will reach EUR4.4 billion by 2006. Well-known mobile entertainment success stories in Japan include NTT DoCoMos IMode. Games that it carries, such as Segas Space Harrier and ChuChu Rocket, will bring in nearly USD830 million this year (Source: Datamonitor). As will be shown below, Human Pacman takes mobile entertainment to a new level of interactivity through its emphasis on seamlessly merging the physical real world with the virtual world, maintaining networked social contacts through out and across the real and virtual world boundaries, and emphasizing physical and tangible contacts with the digital world.

In Human Pacman, I venture to merge the use of computers and the users social interaction as found in the research field of ubiquitous computing. Björk suggested ubiquitous games as a new form of gaming [94] whereby games are played with the computers being embedded in everyday objects, and computing is invisible because there is “intelligent” communication between the objects [71] as defined by Weiser on “ubiquitous computing” (ubicomp). Employing this philosophy, I have implemented a system that embeds everyday physical objects, which seamlessly take on a digital fantasy meaning, throughout the wide area real-world environment. For example, I have attached Bluetooth devices to sugar jars which when being picked up, will automatically communicate with the wearable computer by adding the corresponding virtual ingredient to the inventory list of the player.

Human Pacman ventures to elevate the sense of thrill and suspended disbelief of the players in this untypical computer game. Each of the novel interactions mentioned is summarized in Table 5.1. I will proceed with details to Human Pacman in this article by firstly giving a research background to this system and previous works that have motivated us. Then top level system design is discussed. Next software design of the system is presented. Lastly I proceed to detail gaming experiences involved by clarifying the actual gameplay designed. It is noted that all images that are reproduced from the journal paper [6] are done so with permission from the publisher, Springer-Verlag GmbH.

5.2 Background

Today’s mainstream entertainment revolves around interactivity. Gone are the days when people were satisfied with passive form of entertainment as provided by television and cinema. People today enjoy entertainment they can control, and experience in which they are fully involved [95]. In fact not only do they want such entertainment; people want to enjoy it together with family and friends. As shown in a certain survey [96] one of the top reasons why game players like to play games

Table 5.1: Detail feature descriptions of Human Pacman.

Feature	**Details**
Physical Gaming	Players are physically role-playing the characters of Pacmen and Ghost; with wearable computers donned,they use free bodily movements as part of interaction between each person, between the real and virtual world, and among objects in the real wide area landscapes and virtual environments.
Social Gaming	Players interact both directly with other players when they are in physical proximity, or indirectly via the Wireless LAN network by real-time messaging. There is a perfectly coherent networked social contact among players in both the real and virtual worlds, as well as throughout their boundaries. People from all around the world can also participate in the Human Pacman experience by viewing and collaborating in real-time over the internet with the physical Human Pacmen and Ghosts who are immersed in the physical real world game.
Mobile Gaming	Players are free to move about in the indoor\outdoor space without being constrained to the 2D\3D screen of desktop computers.
Ubiquitous Computing	Everyday objects throughout the environment seamlessly have a real-time fantasy digital world link and meaning. There is automatic communication between wearable computers and Bluetooth devices embedded in certain physical objects used in gameplay.
Tangible Interaction	Throughout the game people interact in a touch and tangible manner. For example, Players need to physically pick up objects and tap on the shoulder of other players to devour them.
Outdoor Wide-Area Gaming Arena	Large outdoor areas can be set up for the game whereby players carry out their respective missions for the role they play. This could even be linked throughout cities.
Seamless Transition between real and virtual worlds	Players swap freely between immersive first person augmented reality view (with virtual cookies and instructions overlay the real world) and full virtual reality view of the Pac-world in the game.

is that game playing is a social activity people can enjoy with family and friends. With advancement in networking technology, social gaming has gained popularity since the introduction of networked games [96]. Networked games overcame the barrier of distance, enabling real people to play against each other over large areas. After all there is no opponent like a live opponent since no computer model will rival the richness of human interaction [97].

According to a recent study by Nezlek [98], enjoyable and responsive interactions increase life satisfaction scores among people. Nevertheless, even in networked computer games, social interaction between players is limited since natural interactions such as behavioral engagement, and cognitive states are lost. Thus, by bringing players in physical proximity for interaction, Human Pacman brings networked social computer gaming to a new ground because humans enjoy being physically together, and socially interacting with each other [66]. Essentially, Human Pacman brings the exciting interactive aspects of networked gaming, and merges it with the real physical world, to allow a seamless real-time networked social contact between humans in both the real and virtual worlds simultaneously.

We remember that in pre-computer age, games were designed and played out in the physical world with the use of real world properties, such as physical objects, our sense of space, and spatial relations. Nowadays computer games focus the users attention mainly on the computer screen or 2D\3D virtual environment, therefore constraining physical interactions. However, there seems to be a growing interest in physical gaming and entertainment. Commercial arcade games have recently seen a growing trend of games that require human physical movement as part of interaction. For example, dancing games such as Dance Dance Revolution and ParaParaParadise [99] are based on players dancing in time with a musical dance tune and moving graphical objects (see Fig. 5.1). However these systems still force the person to stand in more or less the same spot, and focus on a computer screen in front of them. Nevertheless, our underpinning philosophy is similar. One of the goals for Human Pacman is to bring physical gaming into computer entertainment.

Figure 5.1: A Player at ParaParaParadise Arcade Game.

5.3 Previous Works

Human Pacman has several aspects derived from pioneering work that has been developed on ubiquitous gaming. Multi-players mobile gaming is demonstrated in 'Pirates! [50] (details found in Chapter 2). However, visual and sound effects of gameplay are limited by relatively low computing power of PDAs. Augmented Reality and Virtual Reality cannot be implemented; therefore immersive experience is rather limited due to the flat 2-D display used on PDAs. The E3 project [51] (refer to Chapter 2) on the other hand, focuses on human-to-physical interaction and human-to-human interaction. However it does not explore large-scale configuration where users walk around.

Even though Human Pacman uses augmented reality techniques as part of its interface, it is only for providing a comprehensive user interface for the players. There were some previous works done on using augmented reality in entertainment such as the mentioned AR2 Hockey [47] , and AquaGaunlet [48] . These games are played in a small and restricted area, with limited movement, and little interaction with physical space. The games have no transitions between AR and VR. There is also no exploration on the physical environment the player is in. Another important mobile game is known as ARQuake [49] (also described in Chapter 2), which can be played indoor and outdoor. Although it is a multi-players game, there is little social interactions among the players in the course of the gameplay.

Lastly, the transitions between the real and physical world in Human Pacman is derived from research that has been done on continual transversal along the Reality-Virtuality continuum [75]. Both the Magic Book [100] and Touch-Space [101] are restricted to a small indoor area, there is limited physical movement in gameplay. In Human Pacman, the interface and transition between the real world and virtual world is achieved in real-time throughout the spacious indoor and outdoor physical world.

5.4 System Design

Human Pacman features a centralized architecture that is made up of four main entities, namely the central server, wearable computers, laptops, and Bluetooth embedded objects. An overview of the system structure is shown in the Fig. 5.2 where there is a central server presiding over communications between the Pacmen's computers and their helpers' computers (the same situation applies to the Ghost team's computers). The central server also maintains a common database for the whole system.

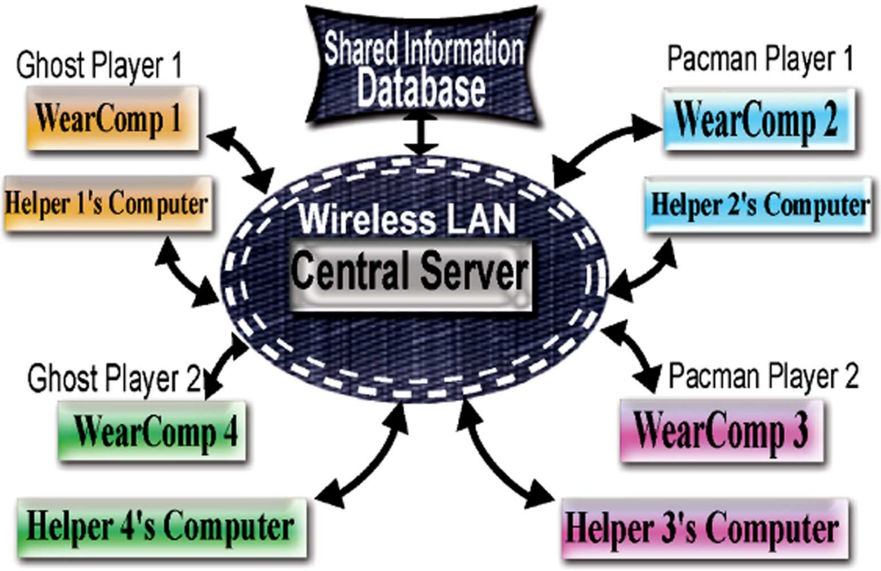


Figure 5.2: Top Level System Design of Human Pacman.

5.4.1 Software Details

The Wireless LAN serves as a communication highway between the wearable computers, the helper computers (laptops), and the server desktop computer. The underlying program is built on a client\server architecture on TCP\IP with wearable computers and helper laptops as clients, and a desktop computer as central server. The software flowchart of the server is shown in Fig. 5.3.

The top level software design of the clients is stated in Fig 5.4. Both helpers' and Pacman\Ghost software structures are identical. The difference being that in

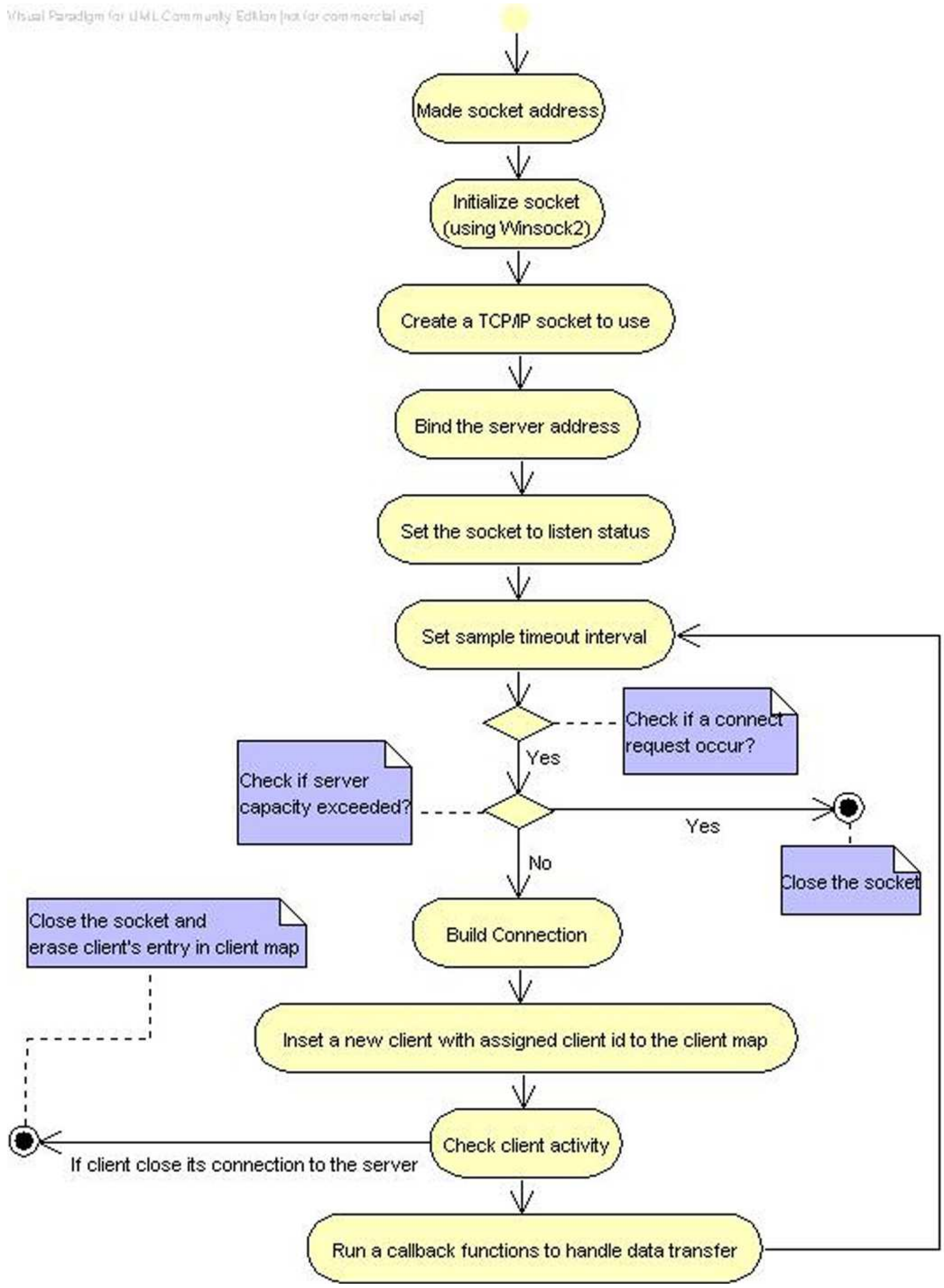


Figure 5.3: Flowchart of software on server.

the former only virtual Pac-World is displayed with no sensors input; while the latter obtains sensors' readings periodically, and is able to display in AR mode with camera video stream overlay.

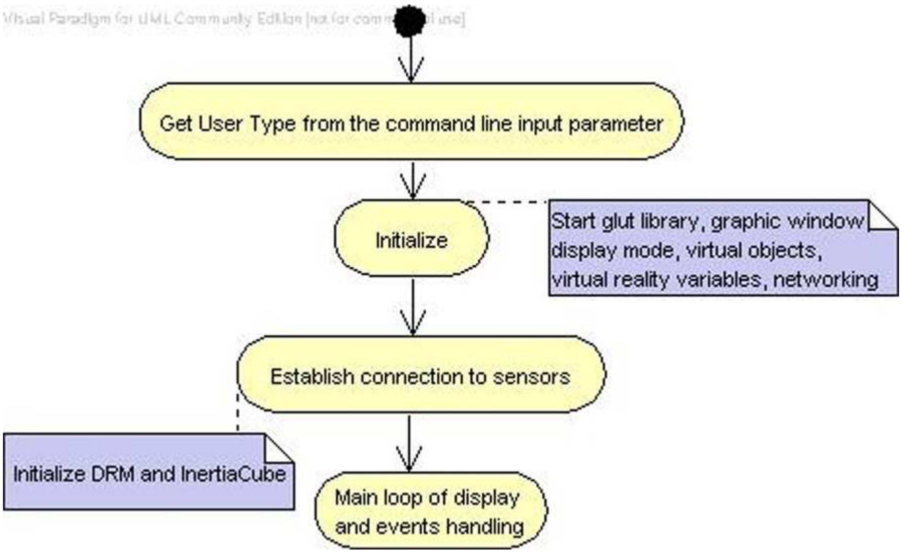


Figure 5.4: Top level flowchart of software on client.

Fig. 5.5 shows the basic operation of the graphic rendering loop. It must be noted that to enhance the efficiency and performance of the program, I have implemented multi-threading in updating process of sensors' data, camera capture and client\server networking. Modularity and flexibility of design is maintained for future adaptability and expendability of software.

Physical location and players' status updates are done between the client wearable computers and the server on a frequent and regular basis. The server maintains up-to-the-minute players' information (such as location, status etc.), and presides over any communication between Bluetooth objects and the wearable computers as well as instant messaging between wearable computers and helpers' computers. Thus the data packet transmission and protocol between the server and the wearable and helper computers is very important. The Fig. 5.6 shows the details about the communications between the various parties in the system and the data packets which are transmitted between the various parts of the system.

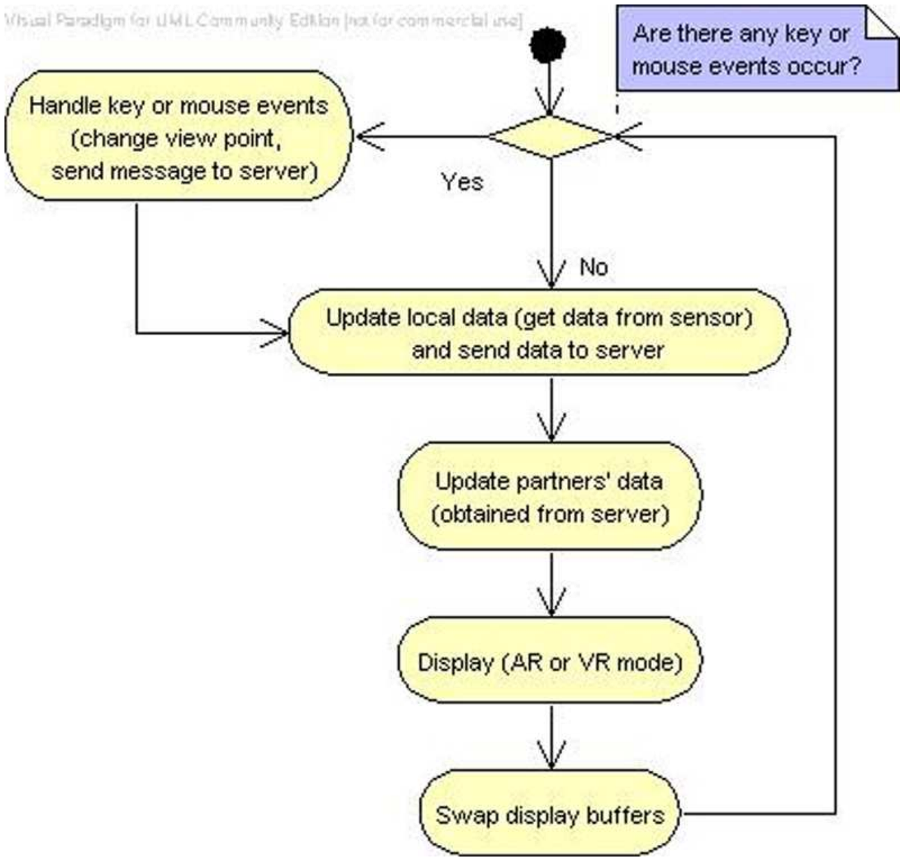


Figure 5.5: Flowchart of client software main loop.

Calculation of Relative Position

The relative position of other players are shown as dials in the AR interface to facilitate players finding one another for exchange of ingredients or information. The calculation is done as detailed in the paragraphs below.

Taking two physical locations as $point1$ and $point2$, the distance d between the two points in radian can be calculated by:

$$d = \cos^{-1}[\sin(lat1)\sin(lat2) + \cos(lat1)\cos(lat2)\cos(lon1 - lon2)]$$

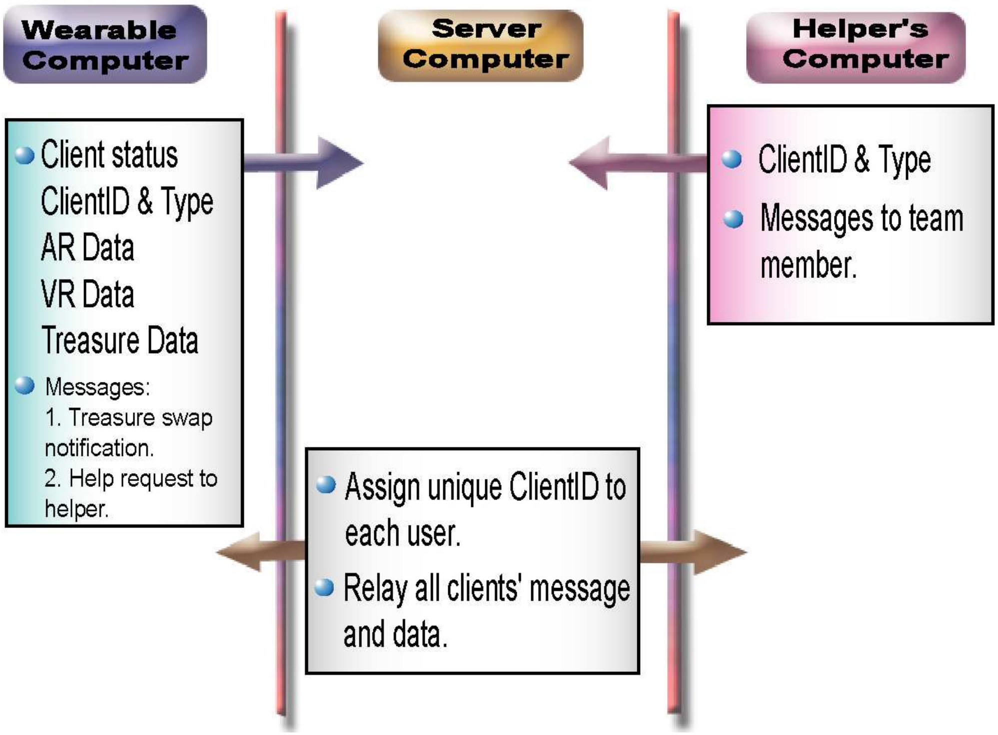


Figure 5.6: Data packet flows between server, wearable computers, and helpers' computers

Where *lon1*, *lat1*, *lon2* and *lat2* are the longitude and latitude of $point1$ and $point2$, respectively which all are in radian. To compute the distance in kilometers instead of radians, d is multiplied by the radius of earth, which is estimated at 6371.0 km.

The course (i.e. the route along which one has moved) *c12* from $point1$ to $point2$ will be calculated as:

IF $\sin(lon2 - lon1) < 0$

$$c12 = \cos^{-1}\left(\frac{\sin(lat2) - \sin(lat1)\cos(d)}{\sin(d)\cos(lat1)}\right)$$

ELSE

$$c12 = 2\pi - \cos^{-1}\left(\frac{\sin(lat2) - \sin(lat1)\cos(d)}{\sin(d)\cos(lat1)}\right)$$

The above *c12* is valid when the *point*1 is facing to the North Pole. Otherwise the yaw of the North Pole for the point1 must be subtracted from *c12*.

5.5 Gameplay

The Wireless LAN serves as a communication highway between the wearable computers, the helper computers (laptops), and the server desktop computer. The underlying program is built on a client server architecture with wearable computers and helper laptops as clients, and the desktop computer as a central server. Physical location and players' status updates are done between the client wearable computers and the server on a frequent and regular basis. The server maintains up-to-the-minute players' information (location, status etc.), and manages any communication between Bluetooth objects and the wearable computers.

The main concepts of the game are first given in terms of team collaboration, ultimate game objectives, and essential nature of the game's playground named Pac-World. Then, I move on to present the details on the players' roles as Pacman, Ghost, and Helper respectively. The calculation of relative positions of players as shown in AR mode is detailed next. I end this chapter by giving examples on several actual gameplay situations.

5.5.1 Main Concepts: Team Collaboration, Ultimate Game Objectives and the Nature of Pac-World

The system aims to provide users with a new human-computer social interaction and entertainment experience. Users will feel great excitement when moving around in physical space and interacting with others as if they have become part of a fantasy world where the virtual Pac-World and the real world have become one.

Team Collaboration

The players are assigned to two opposing teams, namely the Pacman team and the Ghost team. The former consists of two Pacmen and two Helpers; correspondingly, the latter consists of two Ghosts and two Helpers. Each Pacman\Ghost is in coalition with one Helper. The interactive advantage of the helpers is that people from all around the world can participate in the Human Pacman experience by viewing and collaborating in real time over the internet with the physical Pacman and Ghost who are immersed int he physical real world game. Note that all characters, the Pacman, Ghost, and Helpers, are in fact real persons who are engaged in this wide area interactive entertainment system.

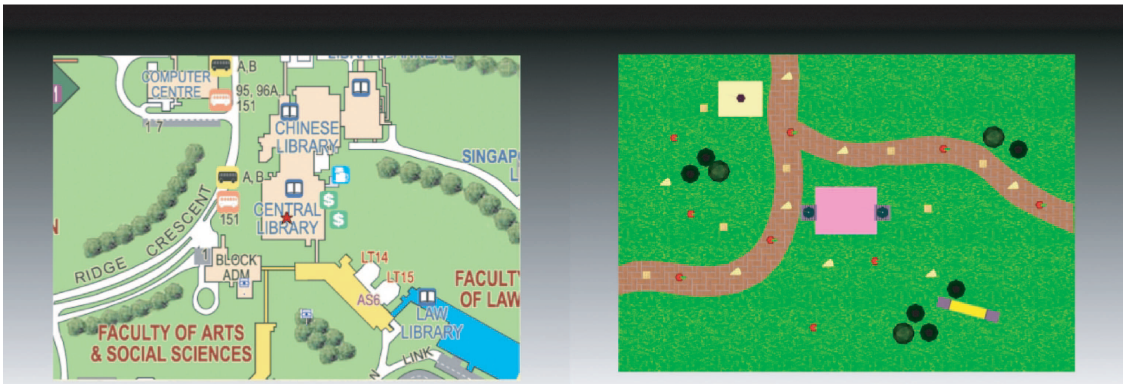
Ultimate Game Objectives

Ever since its introduction by Namco to Japanese arcade fans in 1979, Pacman has gone through numerous stages of development yet the ultimate goal of the game remains fundamentally unchanged. I have designed Human Pacman to be in close resemblance to the original Pacman in terms of game objectives so that the players' learning curves are very much levelled to the point that they can pick up the game in no time and enjoy the associated familiarity. Basically the goal of the Pacman team is to collect all virtual plain cookies and hidden ingredients in Pac-World while avoiding the Ghosts. On the other hand, the aim of the Ghost team is to devour all Pacmen in the Pac-World. To add to the excitement of gameplay, after 'eating' certain special ingredients, a Pacman gains Ghost-devouring capability and henceforth can attack her enemy head on for a limited period of time.

The Nature of Pac-World

Pac-World is a fantasy world existing dualistically in both Augmented Reality (AR) and Virtual Reality (VR) mode. Pacmen and Ghosts, who are walking around in the real world with their networked wearable computers and head mounted displays (HMD), are allowed to switch between the two viewing modes. Helpers, on the other hand, can only view in VR mode since they are stationed in front of networked computers. Most importantly there is a direct and real-time link between the wide-area physical world and the virtual Pac-World at all times, thus providing the users with a ubiquitous and seamless merging of the fantasy digital world and the realistic physical world. As seen in Fig. 5.7 where the 2D map of the selected gameplay area in our university campus in Singapore and the 3D map of Pac-World are shown side-by-side. The virtual path's width is about half that of the real road. The part of the virtual path that has seemingly gone over the 'Chinese Library' in the real world is due to the low resolution in the real world map which does not show the pedestrian footpath that links the main roads and the groundfloor of the library. I have converted the real world to a fantasy virtual playground by ingraining the latter with direct and perceptible physical correspondences. This marvel is achieved using two sensor modules, namely the Dead Reckoning Module (DRM) and InertiaCube2 (details about the sensors are described in Chapter 2 and Chapter 3).

By placing the InertiaCube2 on the cap of each player, her head movement and orientation is tracked to high accuracy. Consequently using the player's position (from DRM) and head movement, the wearable computer calculates the relative position of each plain cookie within the view of the camera, and superimposes a 3-D virtual cookie image of a proportionate size on corresponding position on the



2D Map of Physical Space for Pac-World

3D Map of Virtual Pac-World

Figure 5.7: 2D Map of Game Area and Its Corresponding 3D Map of Pac-World.

video stream. The position of other mobile players obtained from the server is used to update the 2-D virtual map in the HMD view of the player. Similarly the point-of-view of each mobile player is sent to the computer of a helper through the server, and the corresponding view in the virtual Pac-World can be displayed.

Virtual cookies are scattered in a maze-like manner (for example on real footpath) over the real physical game area and are waiting to be collected by the Pacman. They are displayed in the first person perspective of the player, dependent on her physical position and head motion. The player sees cookies on the footpath, just as if she were a real pacman in a Pacman maze. This provides a sense of presence and immersion with the virtual Pac-World, as well as a feeling of active participation in the real world. The real-time position of each mobile user is sent periodically to the server through wireless LAN. Upon receiving the position data, the server sends an update to each wearable computer the position of other mobile players, as well as the positions of all "non-eaten" plain cookies.

5.5.2 Pacman, Ghost, and Helper

Pacman has to physically move around the game area attempting to collect all virtual cookies. When she is in AR mode, through the HMD, she sees the real world being overlaid with virtual plain cookies as shown in Fig. 5.8. Video streams of the real world are sent real-time to the HMD to enable players to navigate freely in the physical world.

Pacman 1 Details:
Wealth 24
Life
Message:
Yaw 115.6300
Pitch 0.7800
Roll 3.8600
Pacman 2
Status: Normal
Position: Lat: -8.39 Lon: -2.73

Figure 5.8: First Person View of Pacman.

In addition to the virtual plain cookies, she has to find and collect physical ingredients that are actually Bluetooth embedded objects as shown in Fig. 5.9. These objects have direct links and representations in the virtual Pac-World. When Pacman is in AR mode, she is able to see ally player in the map on the lower left corner of the display. She is able to gauge the relative position of her ally from the compass on the right corner so as to look for her for the exchange of ingredients via Bluetooth communication.

Figure 5.9: Bluetooth Embedded Object.

On the other hand, the Pacman should avoid being devoured by Ghost, i.e. not letting Ghost tapping on her shoulder where the capacitive sensor is attached on. This physical touch interaction between the players exemplifies tangible physical interaction between humans, which is commonly found in traditional games such as hide-and-seek and the classic "catching" game, but is now being revived in computer gaming arena.

It is noted that enemy units and hidden ingredients are not displayed on the map. This makes the game more challenging with the added element of surprise. Ghost players can sneak behind a Pacman and pounce on her without her realizing.

The AR mode provides a sense of physical presence and immersion in the Pac-World which is merged with the real world. However in some aspects, because of the fact that our bodies have limited speed and no ability to fly, the VR mode provides benefits that cannot be achieved in the AR mode. For example, the player can “fly up into the sky” and look down to see where all her fellow allies are. The can be achieved in a first person VR viewpoint.

In the VR Pac-world, players become immersed completely in a VR world. A Pacman or Ghost can switch to VR mode at will by clicking a button on the wearable computer. The AR HMD display is replaced with an egocentric view of how the real world looks like in virtual Pac-World. As seen in Fig. 5.10, each location in virtual Pac-World corresponds to a real position in the physical world, and each player in the real world has a corresponding avatar in the virtual Pac-World at the position determined by the superimposition of both worlds.

Figure 5.10: Real World and the Corresponding Virtual Pac-World.

The role of a Ghost is rather straightforward; she has to track down all Pacmen and devour them. Nevertheless, she has to beware of Pacmen with Ghost-devouring power and avoid being devoured by them.

Helper is a new character in Human Pacman who does not exist in the original Pacman game. Each Pacman and Ghost will be assigned a partner Helper who acts as an intelligence, advisor, and coordinator for her in her quest for achieving her goal. Helpers are viewing the game in real-time from networked computers (which can be anywhere in the world via the Internet) solely in VR mode, regardless of the mode her partner is in. Their views are similar to that of their partners in VR mode, except that they are in third person perspective. They see Pacman and Ghost in their virtual form as shown in Fig. 5.11.

Figure 5.11: Pacman and Ghost Avatars.

To enhance gaming experience for Pacman and Ghost, the players in the physical world with wearable computer are not able to see enemy mobile units (positions of the enemies are not shown in the virtual map, and there is no augmented reality labelling on them) and hidden ingredients when they are in AR mode as mentioned previously. Therefore the Helper, who is always in VR mode and sees all, guides her partner by messaging her with important information as shown in Fig. 5.12 and thus this promotes collaboration and interaction between human.

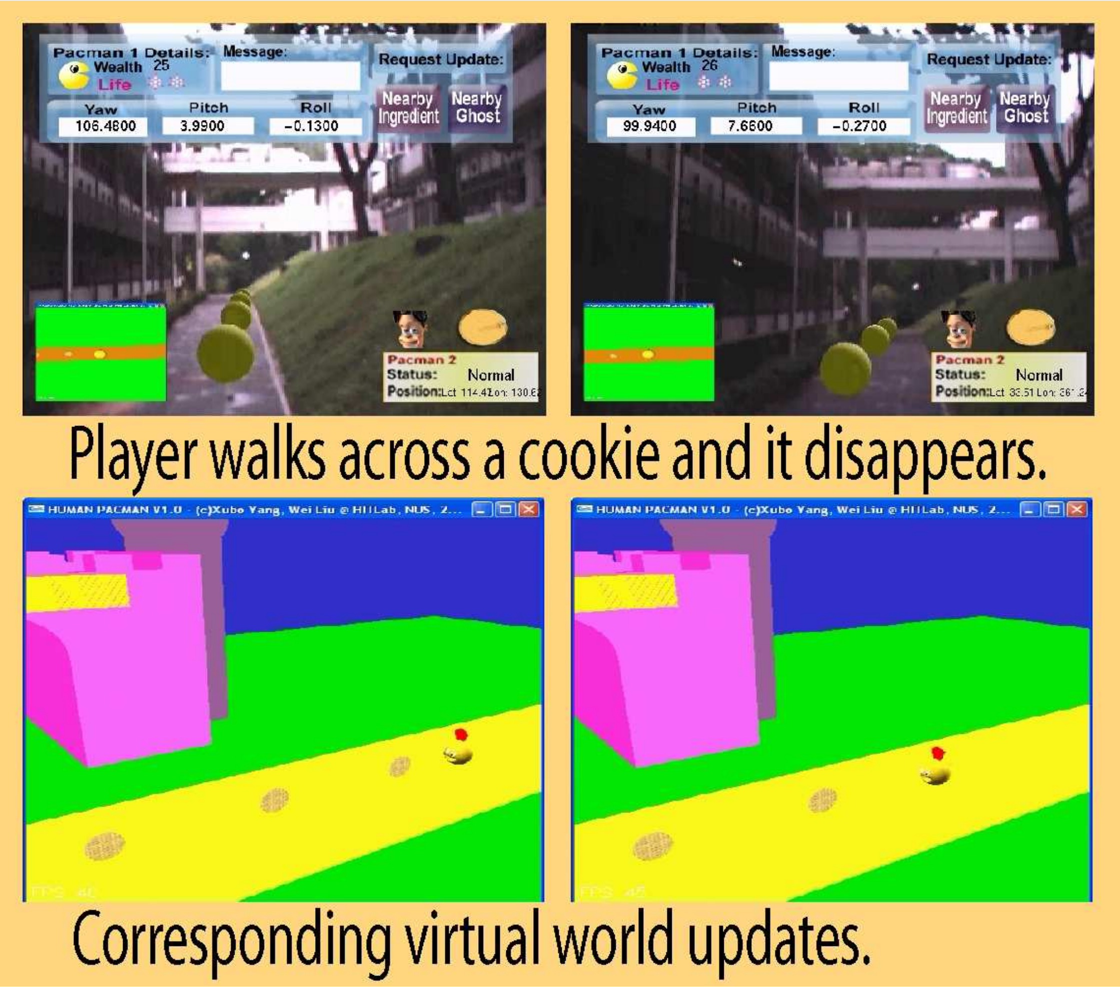
Further social interaction is encouraged through communication between helpers, thus enabling them to coordinate the movements of their partners. For example two Ghost Helpers can collaborate in a plan to corner a Pacman through instructing each of their partnering Ghosts. Social interaction is clearly seen in the team work required between Helpers, between Helper and her partner, and indirectly between ally mobile units.

Figure 5.12: Close Collaboration between Pacman and Her Helper.

5.5.3 Actual Gameplay

Starting the game: Pacmen and Ghosts start from the Pac-castle and Ghost-house in Pac-world respectively. These two places correspond to two different physical locations in the game area.

Collection of plain cookies: Pacman collects a cookie by walking through it. Such physical action is reflected visually in Pac-World through the disappearing of the cookie in both the AR and VR mode. The collection of cookies by a Pacman will be reflected in the Pac-World map seen by all players in real-time, be it on the player's HMD or the helper's laptop. In Fig. 5.13, the top images show the HMD view of the Pacman player as she collects a cookie. When she walks through the cookie, the cookie disappears. Note that this is also reflected in the virtual Pac-World in real-time by the disappearing of the cookie in the corresponding location. This is shown in the images of the figure on the next page.



Pacman 1 Details:
Wealth 25
Yaw 106.4800
Pitch 3.9900
Roll -0.1300

Pacman 2
Status: Normal

Pacman 1 Details:
Wealth 26
Yaw 99.9400
Pitch 7.6600
Roll -0.2700

Pacman 2
Status: Normal

Player walks across a cookie and it disappears.

Corresponding virtual world updates.

Figure 5.13: Pacman Collecting Cookies.

Ghosts are not allowed to collect cookies. Although a Ghost is not able to see enemy Pacman on the map, the disappearing of cookies in her map can give her a hint to where to find a Pacman. Therefore a Pacman has to be careful as her physical interaction with the real world (i.e. movement) can be digitally reflected in the virtual world, and be made used of by a Ghost. Novelty is again seen in such intimate relationship between interaction in the physical world and its effect in the fantasy virtual world. Neither physical distance nor mobility could restrict each player from seeing this effect real-time as all players, including the Ghosts can see an update of the virtual map in real-time.

Collection of ingredients: In the game, Pacmen collects ingredients to make special cookies. Ingredients include flour, butter, sugar, and special ingredients (e.g. Chocolate Chip, Almond). There are two types of special cookies; a butter cookie is made up of flour, butter, and sugar; a super cookie is made up of butter cookie and a special ingredient.

When Pacman eats a butter cookie, she achieves 1 minute immunity from being consumed by a Ghost. When Pacman eats a super cookie, it takes a time lag of 30 seconds before she achieves 3 minutes of ghost-devouring power. (30 seconds is for the Ghost to run or devour the Pacman).

In the game, real Bluetooth-embedded objects are placed in different parts of the game area. In Fig. 5.14 , a sequence of pictures shows a Pacman collecting an ingredient. When the Pacman is within range of the Bluetooth object (about a distance of 10 meters), communication takes place between the wearable computer and the Bluetooth device. The wearable computer sends the unique address of the Bluetooth device to the server, upon receiving it, the server will then decide if the player is eligible to collect the virtual ingredient that is associated with the physical Bluetooth object. If the player is not eligible (for example she has already collected the ingredient), she will not be alerted to the object. Otherwise, an alert message will be shown on the player's HMD display.

The player has to hunt for the Bluetooth embedded object upon receiving the alert message in the surrounding physical area and thus adding elements of fun and adventure to the gameplay. Having found the object, collection is done simply by physically holding the object in her hands. This is achieved by the use of charge transfer sensing on the object that detects the player's touch. I have designed this capacitive sensor using QT161 IC chip from Quantum Research Group [102]. Once haptic data is collected by the sensor, the Bluetooth device embedded on the object will send an alert message to the wearable computer, which will in turn be relayed to the server. The server performs legitimacy check on the player's action, and then proceeds to updating its database as well as informing the wearable computer. The collection of ingredient exemplifies a natural tangible interaction is involved through physically interacting with this object by human touch. Pacman is able to hold a real object naturally in hand as should be in real-life treasure finding. Such tangible action is provides the player a sense of touch to the fantasy domain of gameplay. The collection of the ingredient will be kept in a virtual inventory list and be immediately reflected in the display as well as having the action occurs in real-time in the virtual world. As seen in the figure, collection is shown as an addition of an icon of a sugar jar to the inventory list after the ingredient has been collected. Pacman need not lug the physical object with her as she has collected the ingredient virtually.

Collaboration between players: There is an essential element of collaboration in the gameplay between a Pacman\Ghost with her Helper, and between any allied Pacmen.

(i)Pacman\Ghost and Helper Collaboration– The Helper is in a good position to assist her partner as she has a complete view of Pac-world all the time, including the

Figure 5.14: Sequence of Pictures Showing the Collection of an Ingredient.

positions of all players and ingredients. Mobile players can only see the complete Pac-World under the VR mode. However AR mode is more advantageous for mobility because under VR mode, movement is restricted since she does not have a view of the real world. Furthermore as Helpers within the same team are physically close, they are able to collaborate between themselves and work out a strategy to achieve the team's goal. The advantage of this setup is that social interaction and collaboration is significant between Helpers, as well as between Helpers and her partner.

A Pacman\Ghost on the move, can send standard messages requesting her Halper to give an update of Ghosts and ingredient locations using the hand-held Twiddler. In response to the request, the Helper sends text messages to

Pacman\Ghost with the requested information. This information is displayed on the top control panel of the mobile unit as shown in Fig. 5.8. With the use of wireless LAN, mobility does not affect the ability of Pacman\Ghost to constantly communication with her Helper. Note that since Helpers can be connected from anywhere in the world via Internet, this configuration allows a global social collaboration with the physical players immersed in the Pac-World.

(ii) Pacman and Pacman Collaboration– Pacman players can collaborate through transferring of ingredient between them, when they are physically close to one another with the support of Bluetooth communication. For example Pacman A can initiates request for the list of unused ingredients Pacman B has. Upon approval, A can request for transfer of ingredient from B, subjected to approval by B. Transfer of ingredient is important as Pacman may not be able to comb the whole game area for ingredients. She may lack some ingredients, which may have been collected by her ally. Strategy could be implemented, with the coordination from the Helpers, to distribute ingredients between the Pacmen. However, Pacman are not allowed to transfer special cookies so as not to disadvantage the Ghosts.

Use special cookie: All special cookies can only be used once. When a Pacman consumes a special cookie, she will see an alert message in her HMD, informing her of the power she acquired. Furthermore, in real-time a label describing her acquired-power will be placed on top of her Pacman avatar in the VR mode. This serves to inform all Helpers, including those from the Ghost-team, of her ability. These are illustrated in Fig. 5.15.

Devouring enemy player: To devour a Pacman, a Ghost must physically touch the Pacman's capacitive sensor pads on her shoulders as shown in Fig. 5.16. The same applies when a Pacman with Ghost-devouring capability devours a Ghost. When a Pacman is devoured, she is loses one life point. Each Pacman is given two life

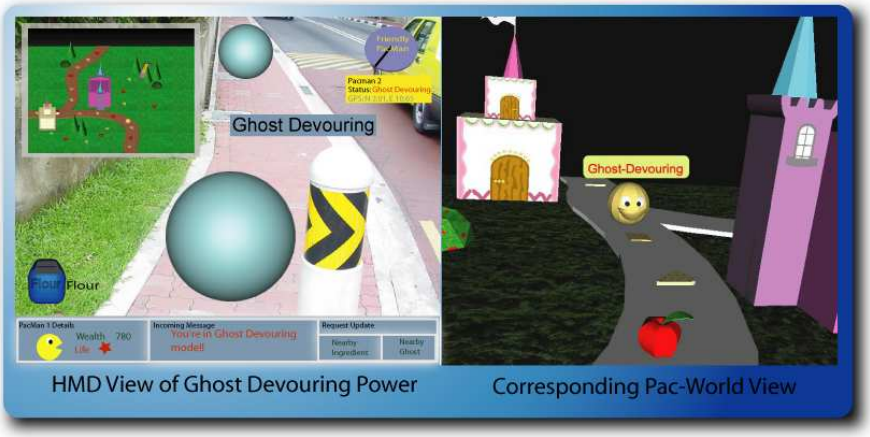


Figure 5.15: Hmd Display and the Corresponding VR Mode View.

points. The same goes for the Ghost. Devouring involves tangible physical touching contact between two players. As close proximity is involved, other forms of human interaction come into play. The act of devouring makes the game more tangible and fun by involving more types of natural physical movement. As in when a Pacman player is the prey, her agility determines the "life-and-death" of her virtual Pacman role. Not only tangibility is brought to play in this fantasy world, but also other human perceptions and instincts. Thus this computer game provides the benefits of natural wide area free bodily movements as part of humanistic interaction between each person.

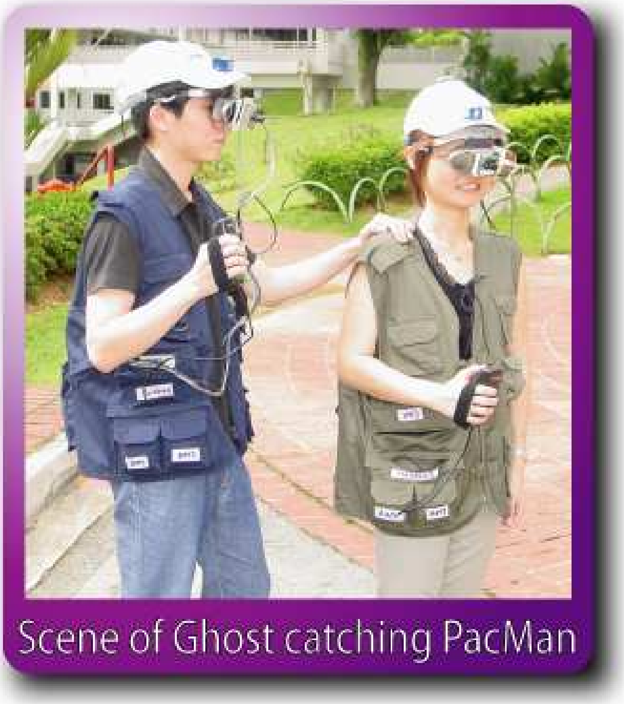


Figure 5.16: Ghost Catching a Pacman.

Ending the game: The game ends when either team meets their goal or when a time limit of fifteen minutes has been reached.

Chapter 6

Software Design and HCI Issues in Human Pacman

Software design is much studied in software engineering literature which examines techniques and practices that help us to build systems. But with the proliferation of mobile computing services, a characteristic of an emerging ubiquitous computing society, there is a real issue with providing a software infrastructure that will support context-aware services. While I ponder on software design problems in mobile computing, not forgetting the bridging problem in our relationship with the computer, i.e. the Human Computer Interface. In fact, the history of computing is peppered with paradigm shifts in how the relationship between humans and computers is perceived. The phenomenon is so well-appreciated that an academic discipline by the name Human Computer Interaction (HCI) has evolved to study how people interact with computers. HCI builds on and complements parts of two other academic disciplines:

- Cognitive Psychology studies the mental processes behind human behavior. That includes such things as perception, learning, accessing information, memory, and problem solving. Each of these mental processes is a factor in computer use.

- Human Factors (or Ergonomics) studies how the design of products affects people. It builds on cognitive psychology and complements this body of knowledge with ergonomics - the study of human capabilities and limitations vis-a-vis tool use - and anthropometry - the study of human body measurements.

In this chapter, I discuss issues bring forth by the inherent feature of AR interface in wearable computing. From mobile service to ubicomp issues, various problems are discussed, especially in the context of mobile entertainment systems (in this case, Human Pacman is used as an example). Then I proceed to detail HCI issues in Human Pacman. The chapter is ended by studying the challenges faced by developers of wearable computing applications so as to provide an insight for future projects.

6.1 Mobile Service and Ubicomp Issues

In recent years, we have witnessed the phenomenal growth of mobile devices. Together with current trends in embedded systems and software, real-time interaction and omnipresent wireless networking, these devices fertilize the formation of a ubicomp landscape, in which digital environments are aware of the presence of users, and communicate with the user via natural interaction means. Human pacman attempts to incorporate a number of mobile and ubicomp elements into the gameplay, for instance mobility, ubiquity, awareness, intelligence, and natural interaction. In this section, I am to examine the various repercussions in the system by studying the three principle features of mobile computing: wireless communication, mobility and portability [103]; following which I will examine two of the interaction themes in Ubicomp, that is tangible interfaces and context-awareness in the context of Human Pacman.

6.1.1 Mobile Computing

From a broader perspective, the game of Human Pacman is a type of user adaptive application that is built upon the infrastructure of wearable and mobile computing, as well as the wireless multimedia communication. It aims to utilize the mentioned technology to provide nomadic players with personalized location based entertainment. However there are numerous problems associated with the actualization of these concepts.

Wireless Communication

Three main problems in deploying the wireless communication network, in this case, the Wireless LAN of IEEE 802.11b, are identified. Firstly disconnections in communication often interrupt the flow of the game. Secondly limitation in bandwidth sets constraints on the type of multimedia data that can be sent between players and between the players and the server. For example I have to use simple text files for the frequent location, perspective, and status updates between the player's wearable computer and the server; and forego with the initial intention of sending live video streams between players. Thirdly unstable outdoor conditions often resulting in high error rate of the network. These three factors in turn increase communication latency which is due to retransmission, retransmission on time-out delays, error control processing, and short disconnections. Therefore it is rather difficult to maintain Quality of Service (QoS), especially when players accidentally move beyond the coverage of the network, or move into areas of high interference. I try to minimize the problems by carefully selecting the area for gameplay in the vicinity of the university campus in Singapore where network connectivity is good. Also, when designing the software for the game, I have embedded components that enable continual processing based on local data on the wearable computer so that when short disconnections occur, the game can still proceed without much disruptions. Lastly, the client/server communication between the server and wearable computers occur in an asynchronous manner in order to reduce the problem of latency.

Mobility

The combination of networking and mobility engender this new form of entertainment system where support for collaborative environment for impromptu communication between mobile players is essential. The dynamism of data, including location and context information from trackers and sensors, contributes much to the volatility of data in the whole system. This creates grave problem when the wearable computer is dozing because of inactivity of players or power failure. Also, with the players moving around in outdoor physical area in this type of wide area mobile gaming, they might move across multiple heterogeneous wireless networks and therefore suffer from address migration interruption between the networks. However, in Human Pacman, these difficulties are avoided by limiting the size of the gameplay area and using single centralized server network architecture.

Portability

Wireless networking with mobile computing has greatly enhanced the utility of carrying a computing device, in this case, a wearable computer. However unencumbered portability is very important for the enjoyability of the game. Conventional portable computing devices like PDAs, and handphone often suffer from the lack of raw processing power and storage size when running multimedia entertainment programs. With the use of custom-built wearable computer, high computing power together with large storage volume are secured for the applications (for details on wearable computer, please see previous section on system design). Another important portability issue is power for the computing device. Since Human Pacman is a game with short duration of play (recommended ten minutes), the wearable computer that is powered by two Sony Infolithium batteries lasting about three hours can adequately manage the task. Last issue in portability is about user interface. Duchamp and Feiner have investigated the use of head-mounted virtual reality displays for portable computers [104]. They conclude with several disadvantage of using the display including the hassle of the head gear, low-resolution, eye fatigue, and the requirement for dim lighting conditions. The problems mention also exist in Human Pacman since head mounted display is used for augmented reality outdoor gaming. Nevertheless as mentioned previously about the short duration of play in Human Pacman, the problem is bearable to the players.

6.1.2 Ubicomp

Ubicomp, also known as “Ubiquitous Computing”, is a phrase which late Mark Weiser (1952-1999) described in 1988 as “calm technology that recedes into the background of our lives”. Though not strictly making computers available throughout the physical environment but invisible to the user as described by Weiser [105], Human Pacman envisions applying the same concept of calm technology into computer gaming by experimenting with tangible interfaces and context-awareness entertainment and communication, which are in fact two of the interaction themes in Ubicomp. Tangible interfaces and context-awareness, which are integral components in the gameplay of Human Pacman, are discussed in the following subsections. Since the game is played in a wide outdoor area, context-awareness issues are studied with focus on outdoor settings.

Tangible Interface

Even though Graphical User Interface (GUI) has been and still is the dominant paradigm for interactions with computers, we are increasingly encountering computation that moves beyond the traditional confines of the desk and attempts to incorporate itself more richly into our daily experience of the physical and social world. Work on physical interaction started to appear in literatures in the early 90s with the introduction of Computer-Augmented Environments [106] that have visioned the merging of electronic systems into the physical world instead of attempting to replace them as in virtual reality environments.

Over the years, a number of projects have explored this new paradigm of interaction termed tangible computing. Early attempts include Bishop's Marble Answering Machine [107] that has made a compelling demonstration of passive marbles as "containers" for voice messages; "Brick" by Fitzmaurice [108] that are essentially new input devices that can be tightly coupled to virtual objects for manipulation or for expressing action (e.g., to set parameters or for initiating processes); "Tangible Bits" and "mediaBlocks" from MIT media lab [72] that allows users to "grasp & manipulate" bits in the center of their attention by coupling the bits with everyday physical objects and architectural surfaces, and “contain, transport, & manipulate” online media using small, electronically tagged wooden blocks that serve as physical icons (“phicons”) respectively. Nevertheless in all of these implementations of tangible computing, computer interaction remains passive with human initiates communication with the tangible objects, and confined only between virtual objects and humans.

However, in Human Pacman, with the use of embedded Bluetooth devices and capacitive sensors, the active communication between computers and human players instantiated by Bluetooth devices is explored, together with graspable interaction between humans and computers, and between human players themselves. Therefore there are two distinctive manifestations of tangible interfaces in Human Pacman; the first is being implemented in ‘Special Ingredient’, which is actually a Bluetooth embedded object with capacitive sensor, and the second is the capacitive sensor shoulder pads on the wearable computers for Pacmen and Ghosts.

Bluetooth is incorporated into the system where there is already Wireless LAN support for communication because firstly it provides paired communication with security which is essential for one-to-one communication between the ‘Ingredient’ and the player; secondly Bluetooth devices support automatic device discovery and connection setup when they are within range therefore provide the backbone for reasoning by close physical proximity in the gameplay. This allows Pacman to search nearby area for ‘Ingredient’ once being alerted of the presence of Bluetooth embedded device. On the other hand, tangible interaction between the Bluetooth embedded object and the player is made possible by using capacitive sensor for detecting the action of touch by the player. In this way, the physical and tactile abilities of Pacmen to support the computational task of registering the discovery and collection of virtual ingredient is harnessed. Another important aspect of this design is the clever exploitation of the affordances of the object's physical properties whereby without prior training, players can intuitively associate the action of picking up the 'Ingredient' object with the collection of it in their virtual inventory as well as having the action simultaneously occur in the virtual world.

The use of capacitive sensor shoulder pads of wearable computer for the detection of 'Devoring' action in gameplay, serves the purpose of demonstrating how computation can be used in concert with naturalistic activities, in this case, the action of physically catching the enemy on the shoulder. Also, by making the distinction between "interface" and "action" very much reduced, i.e. physical action of tapping versus a mouse-click for interaction, Human Pacman allows the players to experience transparent interchange between human and computer as never before in computer gaming.

Context Awareness in Outdoor Environment

Researchers at Olivetti Research Ltd. (ORL) and Xerox PARC Laboratory pioneered the context-aware computing area with the introduction of Active Badge System and PARCTab [109, 110]. However, these systems were expensive with the extensive use of infrared transceivers, and were limited in scope as their applications were confined to an indoor room. With the introduction of GPS and emergence of cheap but accurate sensors, a number of context-aware systems for outdoor applications were built. One notable system was the Georgia Tech Cyberguide project [111] where mobile context-aware tour guide prototypes were made to provide information to a tourist based on her position and orientation. Similarly, at the University of Canterbury, some context-aware fieldwork tools have been developed: an archeological assistant tool [112], a giraffe observation tool [113], and a rhino identification tool [114] to enable the users to make location dependent notes using a PalmPilot as terminal and GPS for positioning. Unlike Human Pacman that uses augmented reality techniques as its main computer interface, these systems have only primitive 2D maps and text presented on palmtops.

Another tourist assistant called Smart Sight was developed at the Carnegie Mellon University [115], which was able to translate from and to local language, handle queries posed and answer in spoken language, and aid navigational around the campus with the use of wearable computers. Nevertheless since laptops were used as part of the mobile computer system, their sheer weight and bulkiness have greatly reduced user's mobility and comfort of use. In Human Pacman, players are provided with custom-built wearable computers that are designed, built, and developed in my lab especially for this application.

The use of GPS and outdoor physical area for computer gaming is pioneered by ARQuake [49] as mentioned in the second chapter. This game is an AR extension of the original desktop Quake game of player shooting virtual monster (in this case the monsters are presented in physical world using AR techniques) in first person perspective.

There are three different ways in which the idea of context awareness is being applied to in Human Pacman. Firstly, with the use of GPS and DRM to provide various data required for tracking the players in wide area outdoor environment, location awareness of the system is made possible. Despite being the most widely publicized and applied location-sensing system, GPS suffers from accuracy and selective availability. The problems are compensated through sensorfusion with DRM. In Human Pacman, I am taking advantage of user's mobility in the wide outdoor area to adapt the system's behavior based on her current location. This location context is being made use of throughout the gameplay for augmented reality (AR) placing of virtual cookies, as well as calculating the relative positions of allied players.

Another important component in realizing AR elements in Human Pacman is the inertia sensor. Through data collected from it, the system is aware of current perspective of the player and thereby displays virtual objects accordingly. Besides, Human Pacman also experiment with information context in Human Computer Interaction with the Helper player having information access to other players via Wireless LAN and providing them with necessary and timely information.

6.2 Human Computer Interaction Design in Human Pacman

In Human Pacman, I tried to combine materials from cognitive psychology and sociology with that from computer science. However the vast amount of issues encountered have exceeded the scope of this thesis. Therefore I will concentrate on discussing issues with respect to Human Computer Interaction design. According to Bellotti [116], there are five questions posing human-computer communication challenges for interaction design. In Table 6.1, I summarize the sensing approaches to interaction in Human Pacman with respect to the five questions raised.

It is by now almost a truism that the concerns and goals of HCI have shifted over the years from a focus on individual interaction between a human and a computer to understanding, designing, constructing and evaluating complex interactive systems involving many people and many technologies. Developments in software and hardware technologies have pushed applications towards supporting our collaborative and communicative needs as social beings, both at work and at play. At the same time, similar developments are pushing the human-computer interface beyond the desktop and into our pockets, streets and buildings. These developments provide exciting challenges and opportunities for HCI. Some of these challenges are addressed in this chapter. Nevertheless, with the hardware technology progressing at breakneck speed nowadays, it can be certain that more HCI issues, as well as ubiquitous computing problems, will surface.

6.3 Challenges of Wearable Computing Applications

To sum up the chapter, I present to readers with several challenges in this field. These are the technologies that must be matured before AR can attain a bright future of assimilating itself in everyone's life:

- *HMD Resolution*: HMDs must offer higher resolution monitors, greater comfort and become less conspicuous (some interesting alternatives to head-worn displays are hand-held AR [118] and monitor-based AR [119]).
- *Tracking*: Future tracking systems may be hybrids, because combining approaches can cover weaknesses of individual sensor. Apart from that, time critical rendering algorithms, such as just-in-time incorporation of tracker measurements, will be developed further for mission critical applications. Even though constructing and debugging real-time systems as such is often painful and difficult, but the requirements for AR demand real-time performance. Side-tracked from main stream sensor tracking, research into eye tracking technologies has the potential to yield registration improvements, and further research is needed into techniques for system delay reduction.

Table 6.1: Five questions and answers posing human-computer communication challenges for interaction design in the case of Human Pacman.

Basic Question	**Human Pacman Interaction Answers**
Address: How do I address one (or more) of many possible devices?	With the implementation of ubiquitous computing, the system constitutes a more amorphous concept with automated interactions between sensors and computer. The existence of unique address for each Bluetooth device disambiguates the Bluetooth embedded objects. Furthermore, centralized control of the server prevents ambiguity of intended target system even when there are more than one players are near the Bluetooth device. Keyboard and mouse are used for messaging and selection of the 'Ingredients' to be exchanged between Pacmen.
Attention: How do I know the system is ready and attending to my actions?	Graphical feedback is used extensively from providing alert message in popped up window, to refreshing virtual inventory after Pacman picked up Bluetooth embedded object. Also, since this graphical information is provided in the HMD directly in the zone of the user's attention, they are highly effective.
Action: How do I effect a meaningful action, control its extent and possibly specify a target or targets for my action?	The Pacman\Ghost click on preset messages to be sent to Helpers. Pacmen click on graphical representation of 'Ingredient' to be exchanged. Clearly labeled Bluetooth embedded objects are to be found in physical space where interaction is intuitive. According to Norman's Theory of Action [117], this form of tangible interface bridges the 'Gulf of Execution'.
Alignment: how do I know the system is doing (has done) the right thing?	Real time graphical feedback presents distinctive and timely graphical elements establishing the context of the system.
Accident: How do I avoid mistakes?	Pacman right-click on virtual ingredient in order to dump the ingredient.

- *Perceptual and Psychophysical Studies*: Augmented reality is an area ripe for psychophysical studies. How much lag can a user detect? How much registration error is detectable when the head is moving? Besides the questions on perception, psychological experiments that explores performance issues are also needed. For example, how much does head-motion prediction improve user performance on a specific task? Furthermore, not much is known about the potential optical illusions caused by errors or conflicts in the simultaneous display of real and virtual objects [30].

- *Portability*: AR applications require giving the user the ability to walk around large environments, even outdoor as demonstrated by the projects in this thesis. This requires making the equipment self-contained and portable. Therefore practical AR systems will rely heavily on the development of wearable computers.
- *Social and Political Issues*: Technological issues are not the only ones that need to be considered when building a real application. There are also social and political dimensions when pushing new technologies into the mass market. Sometime, perception is what counts, even if the technological reality is different. Ergonomics and ease of use are of paramount considerations. Although technology transfer is not normally a subject of academic concern, it is a real problem. Social and political concerns must be addressed during attempts to move AR out of the research lab and into the hands of real users.

Chapter 7

Summary

This thesis has described the development of an advanced wearable computer system named "DSTAR". It is a fully functional, self-powered, self-contained computer that is worn on the body. Designed for mobile applications, this wearable computer is capable of providing access to information, and interaction with information, anywhere and at anytime. Making use of augmented reality as an advance interface to the wearable computer, I have constructed several novel applications in an attempt to establish wearable computing as the next paradigm shift in computer technology. I have explored the area of mobile computing by design computer games based on wearable computer platform. The applications has also various novel features such as the support for tangible interaction with Bluetooth embedded objects, Wireless LAN real-time communication, and seamless transition along the Virtuality-Reality spectrum.

The main goal in the first two projects in this thesis, 'Game City' and 'Interactive Theater', is to explore future MR and wearable computing technologies involving new styles of applications. I envision a new type of game experience that has two main features: integrated ubiquitous context-awareness and sociality into the computer interaction context, which entails ubiquitous, tangible, and social computing (and thus directly applies the theory of embodied interaction); and a seamless merging of physical world, augmented world and virtual world exploration experience.

The ubiquitous computing theory has put into practice in the domain of work, but much less work has been conducted in the domain of play and the field of artistic expression. Similarly, mixed reality technology has been investigated as an ideal collaborative interface to addresses major issues in CSCW (computer supported collaborative work), seamlessness and enhancing reality [120], but little work has been conducted to apply mixed reality technology to play and entertainment. Therefore by integrating mixed reality with embodied computing elements, which stresses human to physical world interaction and human to human interaction, I hope to improve on CSCE (computer supported collaborative entertainment) - a tangible and social computing wearable computer based Mixed Reality.

Digital information is embedded in the environment, in objects, and in the background of the play space with ubiquitous computing. Through tangible computing, players will be able to collaboratively play on shared virtual models by manipulating or co-manipulating tangible interfaces rather than using non-tangible icons or menus. Participants can collaborate in a more natural, socially organized way with other collaborators in the mixed reality entertainment space. Furthermore, the real-time and real-space activities of the players as social beings are placed at primary importance. Thus, the real-world environment is an essential and intrinsic entertainment element and the human's physical context influences the events in the game or theater.

The third application developed, 'Human Pacman', is fundamentally an extension of the previous ideas. I have observed that the continual propagation of digital communication and entertainment in recent years has forced many changes in societal psyche and lifestyle, i.e. how we think, work and play. With physical and mobile gaming gaining popularity, traditional paradigms of entertainment will irrevocably shake from the stale television-set inertia. I believe that 'Human Pacman' heralds the conjuration and growth of a new genre of computer game that is built on mobility, physical actions and the real world as a playground. Reality, in this case, is becoming more exotic than fantasy because of the mixed reality element in the game play. On the other hand, emphasis on physical actions might even bring forth the evolvement of professional physical gaming as competitive sport of the future, for example 'PacMan International League'.

Element of social gaming in 'Human PacMan' symbolizes the nascence of humanity in future digital entertainment. People are looking forward to widening their circle of friends and colleagues through social collaboration in game play. A new form of interactive entertainment is evolved.

Another important area of impact is the field of education. The technology presented in 'Human PacMan' can be exported to applications in educational training that stresses on "learn by experience". Students are immersed in real site of action, and are given instructions visually through head mounted display or verbally through speaker\earphone. This technology serves as a powerful instrument of cognition since it can enhance both experimenting and reflective thoughts through mixed reality and interactive experience.

In short, I believe 'Human Pacman' is a pioneer in the new hybrid of physical, social, and mobile gaming that is built on ubiquitous computing and networking technology. The players are able to experience seamless transition between real and virtual world and therefore a higher than ever level of sensory gratification are obtained.

In conclusion, I summarize the contributions of this thesis in Table 7.1.

Table 7.1: Contributions of Thesis.

TOPIC	DETAIL DISCUSSIONS
Wearable Computer	1. Discussion on the background of wearable computer and augmented reality. 2. Presentation on several commercial and research wearable systems. 3. Study on components of wearable computer and various software applications that lead to the development of the wearable computer 'DSTAR'. 4. Construction of 'DSTAR' wearable computer. 5. Discussion on technical problems and limitations plaguing current wearable computer technology.
Game City	1. Exploration on the synergy between physical and virtual world with virtual overlay on real world. 2. Stimulating physical and social interaction among players in this computer game. 3. Application of wearable and ubiquitous computing in gaming.
Interactive Theater	1. Construction of a novel embodied computing (ubiquitous computing, tangible interaction, social computing), and mixed reality wearable interactive space for interactive theater. 2. Implementation of 3D live human theater actors in mixed reality.
To be continued...	

Topic	**Detail Discussions**
Human Pacman	1. Realization of the possibility to physically role-playing the characters of Pacmen and Ghosts in physical world. This game introduces mixed reality experience to computer gamers. 2. Exploration on social gaming with players allowed to interact directly (in a face-to-face manner), or via network (Bluetooth, Wireless LAN, and Internet). These traditional features of physical games are revived in computer gaming arena. 3. Reenactment of free bodily movement in computer game using the doctrine of mobile gaming. Players can physically role-playing their characters. This adds a deeper sense of realism to the make-belief gaming world. 4. Implementation of tangible interactions in the application using capacitive sensors with tiny computers. Physical actions are entrenched with digital meanings and consequences. 5. Incorporation of mechanism allowing seamless transitions between virtual and real worlds. This provides the users with a novel experience of being 'transpotting' between the two worlds.
To be continued...	

Topic	**Detail Discussions**
Software Design	1. Study on various mobile computing issues (wireless communication, mobility, and portability) and methods to overcome them. 2. Discussion on ubiquitous computing issues such as tangible interface and context awareness in outdoor environment. 3. Study of various Human Computer Interaction (HCI) issues in the context of Human Pacman. 4. Discussion on challenges of wearable computing applications in general.

Bibliography

[1] S. J. D. Prince, A. D. Cheok, F. Farbiz, T. Williamson, N. Johnson, M. Billinghurst, and H. Kato, “3d live: Real time captured content for mixed reality,” in *International Symposium on Mixed and Augmented Reality*, 2002.

[2] A. D. Cheok, S. W. Fong, X. Yang, W. Wang, M. H. Lee, M. Billinghurst, and H. Kato, “Game-city: A ubiquitous large area multi-interface mixed reality game space for wearable computers,” in *Proc. International Symposium on Wearable Computer (ISWC ’02).* Seattle, WA, USA: IEEE Computer Society, Oct. 2002, pp. 156–157.

[3] A. D. Cheok, W. Wang, X. Yang, S. Prince, S. W. Fong, M. Billinghurst, and H. Kato., “Interactive theatre experience in embodied + wearable mixed reality space,” in *Proc. IEEE / ACM International Symposium on Mixed and Augmented Reality (ISMAR 2002).* Darmstadt, Germany: IEEE Computer Society, Sept. 2002, pp. 59–68.

[4] A. D. Cheok, S. W. Fong, K. H. Goh, X. Yang, W. Liu, and F. Farbiz, “Human pacman: a sensing-based mobile entertainment system with ubiquitous computing and tangible interaction,” in *Proc. of the 2nd Workshop on Network and System Support for Games, NETGAMES 2003.* Redwood City, California, USA: ACM, May 2003, pp. 106–117.

[5] A. D. Cheok, S. W. Fong, K. H. Goh, X. Yang, W. Liu, F. Farbiz, and Y. Li, "Human pacman: A mobile entertainment system with ubiquitous computing and tangible interaction over a wide outdoor area," in *Proc. Human-Computer Interaction with Mobile Devices and Services, 5th International Symposium, Mobile HCI 2003*, ser. Lecture Notes in Computer Science, L. Chittaro, Ed., vol. 2795. Udine, Italy: Springer, Sept. 2003, pp. 209–223.

[6] A. D. Cheok, K. H. Goh, W. Liu, F. Farbiz, S. W. Fong, S. L. Teo, Y. Li, and X. Yang, "Human pacman: a mobile, wide-area entertainment system based on physical, social, and ubiquitous computing," *Personal and Ubiquitous Computing*, vol. 8, no. 2, pp. 71–81, May 2004.

[7] A. D. Cheok, K. H. Goh, F. Farbiz, W. Liu, Y. Li, S. W. Fong, X. Yang, and S. L. Teo, "Human pacman: a wide area socio-physical interactive entertainment system in mixed reality," in *Extended abstracts of the 2004 conference on Human factors and computing systems*, Vienna, Austria, Apr. 2004, pp. 779–780, demonstration Session.

[8] S. Mann, "An historical account of the 'wearcomp' and 'wearcam' inventions developed for applications in 'personal imaging'," Cambridge, Massachusetts, Oct. 1997, pp. 66–73.

[9] R. B. Welch, *Perceptual Modification: Adapting to Altered Sensory Environments.* New York: Academic Press, 1978.

[10] R. Azuma, "Tracking requirements for augmented reality," vol. 36, no. 7, pp. 50–51.

[11] R. Azuma, *SIGGRAPH '95 Course Notes: A Survey of Augmented Reality.* Los Angeles: Association for Computing Machinery, 1995.

[12] S. Mann, "Wearable computing as means for personal empowerment," Fairfax VA, May 1998. [Online]. Available: http://wearcomp.org/wearcompdef.html

[13] E. Thorp, *Beat the Dealer: A Winning Strategy for the Game of Twenty-One*, revised (april 12, 1966) ed. Vintage, 1966.

[14] E. Thorp, "Optimal gambling systems for favorable games," *Review of the International Statistical Institute*, vol. 37, pp. 273–293, 1969.

[15] T. A. Bass, *The Eudaemonic Pie*, H. M. Company, Ed., Apr. 1985.

[16] T. A. Bass. (1998, Apr.) Dress code. Wired Magazine issue 6.04. [Online]. Available: http://www.wired.com/wired/archive/6.04/wearables.html

[17] S. Mann and H. Niedzviecki, *Cyborg: Digital Destiny and Human Possibility in the Age of the Wearable Computer.* Randomhouse Doubleday, 2001, homepage = http://www.wearcam.org/mann.html.

[18] MIT wearable computer: Mithril. [Online]. Available: http://www.media.mit.edu/wearables/mithril/index.html

[19] CMU wearable computers. [Online]. Available: http://www.wearablegroup.org/hardware/index.html

[20] M. D. Fleetwood, M. D. Byrne, P. Centgraf, K. Dudziak, B. Lin, and D. Mogilev, "An analysis of text-entry in palm OSGraffiti and the virtual keyboard," Santa Monica, 2002, pp. 617–621. [Online]. Available: http://www.centgraf.net/graffiti.pdf

[21] T. Starner, "Twiddler2 testtimonials." [Online]. Available: http://www.handykey.com/site/testimonials.html

[22] R. Rosenberg, "Computing without mice and keyboards: Text and graphic input devices for mobile computing," Ph.D. dissertation, University College, London (Dept. of Computer Science), 1998.

[23] B. Wantstall, “Hud on the head for combat pilots,” *Interavia*, vol. 44, pp. 334–338, Apr. 1989.

[24] D. E. Holmgren, “Design and construction of a 30-degree seethrough head mounted display,” University of North Carolina Chapel Hill Department of Computer Science, Tech. Rep., July 1992.

[25] R. Holloway, “An analysis of registration errors in a see-through head-mounted display system for craniofacial surgery planning,” Ph.D. dissertation, University of North Carolina at Chapel Hill, 1994.

[26] J. Fraden, *Handbook of Modern Sensors: Physics, Design, and Application*, 2nd ed. New York: AIP Press.

[27] J. A. Farrell and M. Barth, *The Global Positioning System and Inertial Navigation.* New York: McGraw-Hill, 1999.

[28] A. Janin, K. Zikan, D. Mizell, M. Banner, and H. Sowizral, “A videometric head tracker for augmented reality applications,” in *SPIE Proceedings: Telemanipulator and Teperesence Technologies*, vol. 2351, Boston, Nov. 1994, pp. 308–315.

[29] T. C. D. Kim, S. W. Richards, “An optical tracker for augmented reality and wearable computers,” in *Proc. of IEEE VRAIS ’97*, Albuquerque, Mar. 1997, pp. 146–150.

[30] N. I. Durlach and A. S. Mavor, Eds., *Virtual Reality: Scientific and Technological Challenges.* Washington, DC: National Academy Press, 1995.

[31] E. Foxlin, “Inertial head-tracker sensor fusion by a complementary separate-bias kalman filter,” in *Proc. of IEEE VRAIS ’96*, Santa Clara, Apr. 1996, pp. 185–194.

[32] S. You, U. Neumann, and R. Azuma, “Hybrid inertial and vision tracking for augmented reality registration,” in *Proc. of IEEE VR ’99*, Houston, Mar. 1999, pp. 260–267.

[33] G. Welch, “Hybrid self-tracker: An inertial/optical hybrid three-dimensional tracking system,” University of North Carolina Chapel Hill Department of Computer Science, Tech. Rep., 1995.

[34] S. P. Parker, *McGraw-Hill Dictionary of Scientific & Technical Terms*, 3rd ed. New York: McGraw-Hill, 1984.

[35] B. J. Rhodes, “Remembrance agent: A continuously running automated information retrieval system,” in *Proc. of the First International Conference on The Practical Application of Intelligent Agents and Multi Agent Technology*, London, UK, Apr. 1996, pp. 487–495.

[36] Y. Baillot, D. Brown, and S. Julier, “Authoring of physical models using mobile computers,” in *Proc. Fifth International Symposium on Wearable Computers (ISWC ’01).* Los Alamitos, California: IEEE CS Press, Oct. 2001, pp. 39–46.

[37] A. State, M. A. Livingston, G. Hirota, W. F. Garrett, M. C. Whitton, H. Fuchs, and E. D. Pisano, “Technologies for augmented-reality systems: Realizing ultrsound-guided needle biopsies,” in *Computer Graphics: Proc. SIGGRAPH ’96*, New Orleans, Louisiana, Aug. 1996.

[38] B. Hieb, “The electronic age: The future of wearables.” [Online]. Available: http://www.advancefornp.com/common/editorial/PrintFriendly.aspx?CC=2160

[39] P. Bonato, P. J. Mork, D. M. Sherrill, and R. H. Westgaard, “Data mining of motor patterns recorded with wearable technology,” *IEEE Engineering in Medicine and Biology Magazine*, pp. 110–120, May/Jun. 2003.

[40] “Homepage of Xybernaut Corporation.” [Online]. Available: http://www.xybernaut.com/home.asp

[41] ParkAid: Aiding people with Parkinson’s in everyday life. ParkAid S.r.l. Rome, Italy. [Online]. Available: http://www.parkaid.net/eng/history.asp

[42] D. Siewiorek and A. Smailagic. DiMA: diabetes management assistant wearable computer. From IEEE Pervasive Computing Oct-Dec Issues. [Online]. Available: http://dsonline.computer.org/0212/f/b4wips.htm\#4

[43] M. Billinghurst, J. Savage-Carmona, P. Oppenheimer, and C. Edmond, "The Expert Surgical Assistant: An intelligent virtual environment with multimodal input," in *Medicine Meets Virtual Reality IV*, S. Weghorst, H. B. Sieberg, and K. S. Morgan, Eds. San Diego, CA: IOS Press, 1995, pp. 590–607.

[44] K. Maney. (2002, June) Wearable PCs: A different kind of fashion statement. Fairfax, Va. [Online]. Available: http://www.usatoday.com/tech/techreviews/2001-04-18-wearable.htm

[45] S. Feiner, B. MacIntyre, T. Hollerer, and A. Webster, "A touring machine: Prototyping 3d mobile augmented reality systems for exploring the urban environment," in *Proc. 1st International Symposium on Wearable Computers (ISWC '97).* Cambridge, Massachusetts, USA: IEEE CS Press, Oct. 1997, pp. 74–81.

[46] D. Stricker, P. Dahne, F. Seibert, I. Christou, L. Almeida, and N. Ioannidis, "Design and development issues for archeoguide: An augmented reality based cultural heritage on-site guide," in *Proc. International Conference Augmented Virtual Environments and 3D Imaging (ICAV3D 2001).* Mykonos, Greece: Publishing ZITI, 2001, pp. 1–5. [Online]. Available: http://archeoguide.intranet.gr/papers/publications/ARCHEOGUIDE-ICAV3D01.pdf

[47] T. Oshima, K. Satoh, H. Yamamoto, and H. Tamura, "AR2 hockey system: A collaboration mixed reality system," *Trans VRSJ*, vol. 3, no. 2, pp. 55–60, 1998.

[48] H. Tamura, H. Yamamoto, and A. Katayama, "Mixed reality: Future dreams seen at the border between real and virtual worlds," *Computer Graphics and Applications*, vol. 21, no. 6, pp. 64–70, 2001.

[49] B. Thomas, B. Close, J. Donoghue, J. Squires, P. D. Bondi, and W. Piekarski, "First person indoor\outdoor augmented reality application: ARQuake," *Personal and Ubiquitous Computing*, vol. 6, no. 1, pp. 75–86, 2002.

[50] S. Bjork, J. Falk, R. Hansson, and P. Ljungstrand, "Pirates! - using the physical world as a game board," in *Interact 2001, IFIP TC. 13 Conference on Human-Computer Interaction*, Tokyo, Japan, 2001.

[51] R. L. Mandryk and K. M. Inkpen, "Supporting free play in ubiquitous computer games," in *UbiComp 2001*, Atlanta, GA, Oct. 2001, Workshop on Designing Ubiquitous Computer Games. [Online]. Available: http://www.edgelab.sfu.ca/publications/mandryk_ubicomp.pdf

[52] A. Crabtree, S. Benford, T. Rodden, C. Greenhalgh, M. Flintham, R. Anastasi, A. Drozd, M. Adams, J. Row-Farr, N. Tandavanitj, and A. Steed, "Orchestrating a mixed reality game 'on the ground'," in *Proc. of the 2004 conference on human factors in computing systems*, Vienna, Austria, 2004, pp. 391–398.

[53] Homepage of TIQIT Corporation (maker of matchboxpc). [Online]. Available: http://www.tiqit.com/

[54] Homepage of SaintSong Corporation (maker of espresso pc). [Online]. Available: http://www.saintsong.com.tw/

[55] Homepage of Handykey Corporation (maker of twiddler). [Online]. Available: http://www.handykey.com/

[56] Homepage of MicroOptical Corporation (maker of SV9 viewer). [Online]. Available: http://www.microopticalcorp.com/index.html

[57] IBM Microdrive. [Online]. Available: http://www.microtechint.com/microdrive/

[58] PowerPad product webpage. [Online]. Available: http://www.electrovaya.com/powerpad160.html

[59] Twiddler2 website. [Online]. Available: http://www.handykey.com/site/twiddler2.html

[60] Firefly firewire camera webpage at Point Grey Research. [Online]. Available: http://www.ptgrey.com/products/firefly/

[61] InertiaCube2 from InterSense Corporation. [Online]. Available: http://www.isense.com/products/prec/ic2/

[62] DRMIII dead reackoning module. [Online]. Available: http://www.pointresearch.com/drm3_module.htm

[63] K. Markus and K. Gabriela, "Mems: The systems function revolution," *IEEE Computer Magazine*, pp. 25–31, Oct. 1999.

[64] S. Calmes, S. Schweizer, and P. Renaud, "Lase / optoelectronics '98," *Miniaturized Systems with Microoptics and Micromechanics III*, vol. 3278, pp. 96–102, 1998.

[65] S. You, U. Neumann, and R. Azuma, "Orientation tracking for outdoor augmented reality registration," *Virtual Reality*, pp. 36–42, Nov./Dec. 1999.

[66] J. Bowlby, *Attachment and Loss*, ser. Volume I: Attachment. New York: Basic Books, 1983.

[67] R. Cairns, "Attachment behaviour of mammals," *Psychological Review*, vol. 73, pp. 409–426.

[68] V. Burnham, *Supercade: A Visual History of the Videogame Age 1971-1984*. MIT Press, Oct. 2003, ch. 2.

[69] M. Reite and T. Field, Eds., *The psychobiology of Attachment and Separation.* Orlando, Florida: Academic Press, 1985.

[70] P. Dourish, *Where the Action Is: The Foundations of Embodied Interaction.* MIT Press, Oct. 2001.

[71] M. Weiser, "The computer for the 21st century," *Scientific American*, vol. 265, no. 3, pp. 94–100, 1991.

[72] H. Ishii and B. Ullmer, "Tangible bits: Towards seamless interfaces between people, bits, and atoms," in *Proc. of the Conference on Human Factors in Computing Systems (CHI '97)*, Mar. 1997, pp. 22–27.

[73] L. Suchman, *Plans and situated actions: The problem of human-machine communication.* Cambridge: Cambridge University Press, Nov. 1987.

[74] InterSense Inc. (maker of IS900 system). [Online]. Available: http://www.isense.com

[75] P. Milgram and F. Kishino, "A taxonomy of mixed reality visual displays," *IECE Trans. on Information and Systems (Special Issue on Networked Reality)*, vol. E77-D, no. 12, pp. 1321–1329, 1994.

[76] G. D. Abowd and E. D. Mynatt, "Charting past, present and future research in ubiquitous computing," *ACM Transactions on Computer-Human Interaction*, vol. 7, no. 1, pp. 29–58, 2000.

[77] R. Nakatsu, N. Tosa, and T. Ochi, "Interactive movie system with multi-person participation and anytime interaction capabilities," in *Proc. of the 6th ACM International Conference on Multimedia '98*, Bristol, UK, Sept. 1998, pp. 129–137.

[78] S. Springel, "The virtual theatre, immersive participatory drama research at the centre for communications systems research, cambridge university," in *Proc. of the sixth ACM international conference on Multimedia: Technologies for interactive movies*, Bristol, UK, 1998, pp. 43–49.

[79] M. Craven, I. Taylor, A. Drozd, J. Purbrick, C. Greenhalgh, S. Benford, M. Fraser, J. Bowers, K. Jaa-Aro, B. Lintermann, and M. Hoch, "Exploiting interactivity,

influence, space and time to explore non-linear drama in virtual worlds," in *Proc. of the SIGCHI conference on Human factors in computing systems*, Seattle, Washington, United States, Mar. 2001, pp. 30 – 37.

[80] B. MacIntyre, J. D. Bolter, E. Moreno, and B. Hannigan, "Augmented reality as a new media experience," in *Int. Symp. on Augmented Reality (ISAR 2001)*, New York, Oct. 2001, pp. 197–206.

[81] C. Heath and P. Luff, "Disembodied conduct: Communication through video in a multimedia environment," in *CHI '91 Human Factors in Computing Systems.* New York: NY: ACM Press, 1991, pp. 93–103.

[82] A. Sellen and B. Buxton, "Using spatial cues to improve videoconferencing," in *Proc. ACM CHI 92.* ACM: New York, May 1992, pp. 651–652.

[83] A. Sellen, "Remote conversations: The effects of mediating talk with technology," *Human Computer Interaction*, vol. 10, no. 4, pp. 401–444, 1995.

[84] S. Benford and L. Fahlen, "A spatial model of interaction in virtual environments," in *Proc. European Conference on Computer Supported Cooperative Work (ECSCW'93)*, Milano, Italy, Sept. 1993.

[85] A. Singer, D. Hindus, L. Stifelman, and S. White, "Tangible progress: Less is more in somewire audio spaces," in *Proc. of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, Pittsburgh, Pennsylvania, United States, May 1999, pp. 104–111.

[86] R. Raskar, G. Welch, M. Cutts, A. Lake, L. Stesin, and H. Fuchs, "The office of the future: A unified approach to image based modeling and spatially immersive displays," in *SIGGRAPH 98 Conference Proceedings*, Orlando, Florida, July 1998, pp. 179–188. [Online]. Available: http://www.cs.unc.edu/~raskar/Office/future_office.pdf

[87] T. Ogi, T. Yamada, K. Tamagawa, M. Kano, and M. Hirose, "Immersive telecommunication using stereo video avatar," *Virtual Reality 2001 Conference (VR'01)*, pp. 45–51, Mar. 2001.

[88] A. Laurentini, "The visual hull concept for sillhouette based image understanding," *IEEE PAMI*, vol. 16, no. 2, pp. 150–162, Feb. 1994.

[89] W. Matusik, C. Buehler, R. Raskar, S. Gortler, and L. McMillan, "Image-based visual hullss," in *SIGGRAPH '00 Conference Proceedings*, 2000, pp. 369–374.

[90] D. Myers, "Computer game semiotics," *Play and Culture*, vol. 4, pp. 334–345, 1991.

[91] (2002, Aug.) CIT-online, Communications Update. [Online]. Available: http://www.cit-online.com/info/29082002.htm

[92] C. Schmidt, C. Mines, and D. Bedarida, "Making mobile gaming pay, TechStrategy Report," January 2002.

[93] R. Gear, R. Mokka, and R. Nelson, "Wireless gaming - playing to win, An Ovum Report," January 2001.

[94] S. Bjork, J. Holopainen, P. Ljunstrand, and R. Mandryk, *Special Issue on Ubiquitous Games, Personal and Ubiquitous Computing*, vol. 6, no. 5-6, pp. 358–361, 2002.

[95] "State of the industry - report 2000-2001," Interactive Digital Software Association, 2001. [Online]. Available: http://www.idsa.com

[96] "Essential facts about the computer and video game industry," Interactive Digital Software Association, 2002. [Online]. Available: http://www.idsa.com

[97] C. Crawford, *Live: What a Concept! Networked Games*, ser. Digital Illusion, C. J. Dodsworth, Ed. ACM Press.

[98] J. Nezlek, D. Richardson, L. Green, and E. Schatten-Jones, "Psychological well-being and day-to-day social interaction among older adults," *Personal Relationships*, vol. 9, pp. 57–71.

[99] "Paraparaparadise," Konami Corporation, 2001. [Online]. Available: http://www.konami.com.hk/am/ppp.html

[100] M. Billinghurst, H. Kato, and I. Poupyrev, "Magic book - moving seamlessly between reality and virtuality," *IEEE Computer Graphics and Applications*, vol. 21, no. 3, pp. 6–8, 2001.

[101] A. Cheok, X. Yang, Z. Zhou, M. Billinghurst, and H. Kato, "Touch-space: Mixed reality game space based on ubiquitous, tangible, and social computing," vol. 6, no. 2, pp. 430–442, 2002.

[102] (2002) Quantum Research Group Ltd homepage. [Online]. Available: http://www.qprox.com

[103] G. H. Forman and J. Zahorjan, "The challenges of mobile computing," *IEEE Computer*, vol. 17, no. 4, pp. 38–47.

[104] D. Duchamp, S. Feiner, and G. Q. J. Maguire, "Software technology for wireless mobile computing," *IEEE Network*, vol. 5, no. 6, pp. 12–18, Nov. 1991.

[105] M. Weiser, "Some computer science issues in ubiquitous computing," *Communications of ACM: Special issue on computer augmented environments: back to the real world*, vol. 36, no. 7, 1993.

[106] P. Wellner, W. Mackay, and R. Gold, "Computer Augmented Environments: Back to the real world - Introduction to the Special Issue," *Communications of the ACM*, vol. 36, no. 7, pp. 24–26, July 1993.

[107] C. G. Smith, *The Hand That Rocks the Cradle*. I. D., May/Jun. 1995.

[108] G. Fitzmaurice, H. Ishii, and W. Buxton, "Bricks: Laying the foundations for graspable user interfaces," in *Proc. Conference on Human Factors in Computing Systems (CHI '95), ACM*, Denver, Mar. 1995, pp. 442–449.

[109] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Transactions on Information Systems*, vol. 10, no. 1, pp. 91–102, Jan. 1992.

[110] B. N. Schilit, M. M. Theimer, and B. B. Welch, "Customizing mobile applications," in *Proc. of USENIX Mobile & Location-Independent Computing Symposium*, Cambridge, Massachusetts, Aug. 1993, pp. 129–138.

[111] S. Long, R. Kooper, G. D. Abowd, and C. G. Atkeson, "Rapid prototyping of mobile context-aware applications: The cyberguide case study," in *2nd ACM International Conference on Mobile Computing and Networking (MobiCom'96)*, Rye, New York, Nov. 1996, pp. 97–107.

[112] N. Ryan, J. Pascoe, and D. Morse, *Enhanced Reality Fieldwork: the Context-Aware Archaeological Assistant*, V. Gaffney, M. V. Leusen, and S. Exxon, Eds. Computer Applications in Archaeology, 1997. [Online]. Available: http://www.cs.ukc.ac.uk/pubs/1998/616/content.html

[113] J. Pascoe, N. S. Ryan, and D. R. Morse, "Human Computer Giraffe Interaction - HCI in the Field," *Workshop on Human Computer Interaction with Mobile Devices*, May 1998. [Online]. Available: http://www.cs.ukc.ac.uk/pubs/1998/617

[114] J. Pascoe, N. Ryan, and D. Morse, "Issues in developing context-aware computing," in *Proc. of International Symposium on Handheld and Ubiquitous Computing*, Karlsruhe, Germany, Sept. 1999, pp. 208–221.

[115] J. Yang, W. Yang, M. Denecke, and A. Waibel, “Smart sight: a tourist assistant system,” in *3rd International Symposium on Wearable Computers*, San Francisco, California, Oct. 1999, pp. 73–78.

[116] V. M. E. Bellotti, M. J. Back, W. K. Edwards, R. E. Grinter, C. V. Lopes, and A. Henderson, “Making sense of sensing systems: Five questions for designers and researchers,” in *Proc. CHI 2002, ACM*, Minneapolis, Minnesota, USA, Apr. 2002, pp. 415–422. [Online]. Available: http://web.media.mit.edu/~intille/teaching/fall02/papers/BellottiETAL02%.pdf

[117] D. A. Norman, *The Design of Everyday Things*, V. Gaffney, M. V. Leusen, and S. Exxon, Eds. New York: Doubleday.

[118] V. Klinker, J. Gudrun, H. A. Klaus, E. B. David, P. Chevalier, C. Crampton, D. S. Greer, D. Koller, A. Kramer, E. Rose, M. Tuceryan, and R. T. Whitaker, “Confluence of computer vision and interactive graphics for augmented reality,” in *Presence: Teleoperators and Virtual Reality*, vol. 6, no. 4, Aug. 1997, pp. 433–451.

[119] J. Rekimoto, “NaviCam: a magnifying glass approach to augmented reality,” in *Presence: Teleoperators and Virtual Reality*, vol. 6, no. 4, Aug. 1997, pp. 399–412.

[120] M. Billinghurst and H. Kato, “Collaborative mixed reality,” in *Proc. of the First International Symposium on Mixed Reality (ISMR’99)*, Berlin, 1999, pp. 261–284.