Chapter 11
Designing Outdoor Mixed Reality Hardware Systems

Benjamin Avery, Ross T. Smith, Wayne Piekarski, and Bruce H. Thomas

Abstract Developing usable and robust mixed reality systems requires unique human–computer interaction techniques and customized hardware systems. The design of the hardware is directed by the requirements of the rich 3D interactions that can be performed using immersive mobile MR systems. Geometry modeling and capture, navigational annotations, visualizations, and training simulations are all enhanced using augmented computer graphics. We present the design guidelines that have led us through 10 years of evolving mobile outdoor MR hardware systems.

Keywords Wearable computing · Mixed reality · Augmented reality · Input device · Hardware design

11.1 Introduction

Mixed reality (MR) is a term that encompasses augmented reality (AR), augmented virtuality, and virtual reality (VR). AR is the registration of projected computer-generated images over a user's view of the physical world. With this extra information presented to the user, the physical world can be enhanced or augmented beyond the user's normal experience. The addition of information that is spatially located relative to the user can help to improve their understanding of it. Early work in the field of MR relied on large and bulky hardware that required a user to utilize a tethered display. Users could not walk large distances and this restricted initial MR research. Desirable systems allow users to walk around and explore the physical world overlaid with computer-generated information without being tethered to a fixed location. In an early survey paper on AR, Azuma states that the ultimate goal

---

B. Avery (✉)
Wearable Computer Laboratory, University of South Australia, 5095 Mawson Lakes, SA, Australia
e-mail: ben@benavery.net

E. Dubois et al. (eds.), *The Engineering of Mixed Reality Systems*, Human-Computer Interaction Series, DOI 10.1007/978-1-84882-733-2_11,

of AR research is to develop systems that "can operate anywhere, in any environment" [1]. Our research has focused on aiming toward this goal by making systems that are portable and not limited to small areas.

A pioneering piece of work in mobile MR was the touring machine [5], the first example of a mobile outdoor system. Our group also produced some of the first outdoor prototypes, such as our early Tinmith systems [20]. Using new technology that was small and light enough to be worn, a whole new area of mobile MR research (both indoor and outdoor) was created. While many research problems are similar to indoor VR and AR, there are unsolved domain-specific problems that prevent mainstream AR usage, particularly outdoors. For example, portable systems cannot use some of the more accurate tracking systems available in fixed indoor environments, limiting the fidelity and realism of the AR system (Fig. 11.1). AQ1

The first outdoor MR systems were quite simple in that they relied only on the position and orientation of the user's head in the physical world as the user interface. The virtual environment could be indirectly adjusted via a keyboard or mouse. Without a user interface capable of interacting with the virtual environment directly, the user of these systems is limited to traditional 2D input techniques that are not natural when in an immersive 3D environment. Therefore, as part of our research, we have developed user interface techniques centered around pinch glove technologies [11, 13] that provide more natural interfaces for users. The hardware is a critical part of the design of user interfaces, since limitations of physical devices will affect user interactions.

Many of the hardware components needed to support interactions require miniaturization and concatenation in order to be used comfortably for mobile MR. For example, using an accurate global positioning system (GPS) unit requires a large antenna mounted on the user's head. But to naively mount the antenna would be too large and bulky. Components must be stripped of excess casings and carefully

This figure will be printed in b/w

Fig. 11.1 Tinmith outdoor wearable augmented reality computer

designed into a tightly integrated system. The immersion a user experiences is strongly reduced if the hardware interferes with the user. Much higher immersion can be achieved with a small wearable computer, by reducing the user's awareness of the devices worn.

Miniaturization, integration, and immersion are all related. For an experience to be natural and enjoyable, the hardware needs to be designed to support the user interface. This chapter focuses on the design of the hardware that is necessary to support mobile outdoor mixed reality systems. Research-based mobile MR systems built in the past used off-the-shelf components attached to a framework like a backpack or vest, allowing them to be easily built and modified [3]. However, these systems are cumbersome, heavy, and fragile. Currently there are no commercially available all-in-one systems available for mobile outdoor MR.

This chapter presents design guidelines we have developed for building outdoor mobile MR computers gained during our 10 years of experience [12, 20]. A history of our wearable mixed reality backpack computers is shown in Fig. 11.2. Readily available hardware such as GPS units, hybrid orientation tracking sensors, and laptop computers are combined using custom electronics allowing intuitive human–computer interactions to be performed. These design guidelines cater for systems to be robust, lightweight, and usable, but also take into account important practical considerations related to usability and debugging.

Fig. 11.2 1998–2007: 10 years of Tinmith outdoor wearable computers

This figure will be printed in b/w

11.2 Previous Work on Outdoor MR

While indoor examples are useful, the ultimate goal of MR research is to produce systems that can be used in any environment with no restrictions on the user. Mobile outdoor MR pushes the limits of current technology to work toward achieving the goal of unrestricted environments.

The Touring Machine, developed by Feiner et al. from Columbia University [5], is based on a large backpack computer system with all the necessary equipment attached. The Touring Machine provides users with labels that float over buildings, indicating the location of various buildings and features at the Columbia campus. Interaction with the system is achieved through the use of a GPS and head compass to control the view of the world. By gazing at objects of interest longer than a set dwell time the system presents additional information. The Touring Machine was then extended by Hollerer et al. for the placement of what they termed situated documentaries [8]. This system shows 3D building models overlaying the physical world, giving users the ability to see buildings that no longer exist on the Columbia University campus. Additional media features were added, such as the ability to view video clips, 360° scene representations, and information situated in space at the site of various events that occurred in the past.

The Naval Research Laboratory is investigating outdoor MR with a system referred to as the Battlefield Augmented Reality System (BARS), a descendent of the previously described Touring Machine. Julier et al. describe the BARS system [9] and how it is planned for use by soldiers in combat environments. In these environments, there are large quantities of information available (such as goals, waypoints, and enemy locations) but presenting all of these to the soldier can become overwhelming and confusing. The BARS system has also been extended to perform some simple outdoor modeling work [2]. For the user interface, a gyroscopic mouse is used to manipulate a 2D cursor and interact with standard 2D desktop widgets.

Nokia research has been performing research into building outdoor wearable MR systems, but with 2D overlaid information instead of 3D registered graphics. The Context Compass by Suomela and Lehikoinen [18] is designed to give users information about their current context and how to navigate in the environment. Two-dimensional cues are rendered onto the display. To interact with the system, a glove-based input technique named N-fingers was developed by Lehikoinen and Roykkee [10]. The N-fingers technique provides up to four buttons in a diamond layout that is used to scroll through lists with selection, act like a set of arrow keys, or directly map to a maximum of four commands.

More recently MR research has moved to include a strong focus on handheld devices. The advances in processing power and inclusion of built-in cameras on mobile phones have made it possible to render registered 3D augmentation on a mobile phone. Schmalsteig and Wagner extended their existing MR framework to create Studierstube ES, an MR framework and tracking solution for mobile phones and handheld devices [16]. Handheld devices are able to track the location of fiducial markers and display augmentations over a video image on the display. Devices were deployed at two museums with MR games and learning applications.

11.3 The Tinmith System

Tinmith is the software architecture that runs on our wearable MR systems. The Tinmith system supports a number of novel user interfaces that allow users to interact with their virtual surroundings. Tinmith was the first system developed with 3D interactions appropriate for an outdoor setting. Other backpack systems, such as the Touring Machine, focused on traditional 2D techniques. These other backpack systems employed 2D input devices (tablets and handheld trackballs) and used standard workstation mappings from 2D devices to 3D virtual data. Tinmith discarded the traditional desktop interaction metaphor (keyboard and mouse), instead designing the interface to take advantage of the 3D nature of the environment. An interface based on thumb-tracked pinch gloves uniquely combines command entry and dual cursor control to provide a complete user interface solution. Enabling users to gesture with their hands for pointing and selecting menu options is a more natural interface for outdoor interactions. The system supports creating 3D models of new and existing structures with a set of techniques termed construction-at-a-distance techniques. These techniques include AR working planes, infinite carving planes, laser carving, laser coloring, texture map capture, and surface of revolution. An overview of the Tinmith user interface is provided in this section. An in-depth presentation of the construction techniques is available in [13].

The user interface is made up of three components: a pointer controlled by the tracking of the thumbs with a set of gloves worn by the user; a command entry system where the user's fingers interact with a menu for performing actions; and an MR display that presents information back to the user [14]. The interface is shown in Fig. 11.3. The display for the interface is fixed to the head-mounted display (HMD) screen with menus on the lower left and right corners. The eight commands in blue are mapped to the fingers and the user activates a command by pressing the appropriate finger against the thumb. When an option is selected, the menu refreshes with the next set of options that are available. Ok and cancel operations are activated by pressing the fingers into the palm of the appropriate hand and are indicated in the topmost green boxes of the menus.

AQ2

The interaction cursors are specified using fiducial markers placed on the tips of the thumbs, visible in Fig. 11.6. The cursors can be used for manipulating virtual objects (a move operation on a virtual tree is being performed in Fig. 11.3). The user moves the cursor over a virtual object in the scene and selects the appropriate menu command to begin the move operation. The object is attached to that cursor and moved around freely by the user moving their hand. Another menu option is used to place the virtual object. More complex interactions are performed by using both the left and right thumb cursors simultaneously. Scaling of objects is achieved by moving the cursors closer together or further apart. Rotations are performed by moving one cursor in an arc around the second cursor.

This figure will be printed in b/w

(4) Tinmith display captured
(3) Tinmith display captured
(2) No clipboard found for selected object
(1) Tinmith display captured

Fig. 11.3 The Tinmith user interface displays menus in the bottom corners of the screen. The user can move objects such as a virtual tree with tracked thumbs

The modeling and interaction techniques have to be strongly supported by the hardware. Tracking the location of the hands requires a high-quality camera for vision tracking and the modeling techniques require accurate tracking of the user location and orientation. At the same time the user needs to be sufficiently mobile to freely move around and perform the techniques. It is desirable for the MR system to be lightweight so it may be worn comfortably while performing tasks.

11.4 Hardware for Outdoor MR Systems

Outdoor MR is commonly performed in one of two ways, using handheld or immersive hardware technologies. Handheld MR is achieved by rendering a camera view and overlaid computer graphics on a handheld device such as a mobile phone or PDA. MR with an HMD allows images to be overlaid directly on the user's view of the world achieving a higher level of immersion. When used with a specialized wearable computer the user is able to freely walk around and explore a mixed reality environment. Recent trends have been moving toward the use of handheld over immersive hardware. And although we are investigating the use of handheld systems, currently we use immersive hardware as it provides greater flexibility and a more interactive experience. In particular both the user's hands remain free to support complex bimanual interactions. In comparison handheld systems tend to require the non-dominant hand to hold the hardware while the dominant hand interacts with the system [6].

Creating an MR overlay that is accurately registered to a user's view requires three primary devices: computer, display, and a tracker. The computer generates 3D graphics that are rendered to the display. The tracker is used to determine where the graphics are rendered to achieve correct registration.

When using HMDs for outdoor MR, video see-through and optical see-through are the two common techniques used to achieve the augmented environment. Video see-through uses a camera attached to the HMD to capture the real world view. The camera's video stream is combined with the virtual graphical objects with the graphics hardware and displayed on the HMD. Optical see-through instead uses a half-silvered mirror to combine the real world view and the computer display. Although current research is investigating techniques to improve the brightness of optical see-through displays, we have found the limited brightness does not provide a satisfactory image, particularly when using the system in bright sunlight. A notable exception is virtual retinal displays. To date this technology only produces a single color, red, with varying levels of intensity.[1]

The translation and orientation of the user's head needs to be accurately tracked. A wide variety of tracking technologies are available for indoor use including magnetic, vision based, inertial, or ultrasonic. However, the choices available when working outdoors are significantly more limited. Magnetic trackers such as those from Polhemus[2] or vision tracking algorithms such as the going out system by Reitmayr et al. [15] can be used outdoors but have very limited range and require preparation to make the area suitable for tracking (such as installing sensors or modeling the environment). GPS is the only suitable position tracking technology for use outdoors that supports an unlimited tracking area in open spaces and does not require previous preparation of the environment. We use survey-grade GPS units for position tracking, and an Intersense InertiaCube3 for orientation tracking. The InertiaCube3 uses magnetometers, accelerometers, and a gyroscope to track position relative to magnetic north and gravity.

AQ3

A common construction approach used when building wearable computer systems is to electrically connect off-the-shelf components and place them in a backpack or belt. This design method leads to cumbersome, bulky, and unreliable systems. An alternative approach is to remove the required electronic components from their casings and permanently install them into a single enclosure, hardwiring each of the components together. This increases robustness, decreases size and weight, and if carefully designed can maintain expandability. We currently have two generations of compact wearable MR systems, the 2005 and 2007 designs shown in Fig. 11.2.

---

[1] http://www.microvision.com

[2] http://www.polhemus.com

This section discusses the components and construction required to achieve MR on mobile wearable computer system. First the head-mounted electronics that contains the display and trackers is presented, followed by discussion of the main enclosure that holds the computer and additional required electronics and battery requirements.

11.4.1 Head-Mounted Electronics

Many essential electronics in outdoor MR systems are mounted on the user's head. These components include the HMD, camera, GPS antenna (or entire GPS unit), orientation sensor, and often power regulation electronics. The tracking sensors need to be rigidly attached to the HMD to ensure correct registration of the MR graphics. We use a monoscopic HMD and single camera for a number of reasons. Stereo displays require two renders of the virtual scene, one for each eye display. For indoor systems this is possible by using a PC with multiple graphics cards; however, for a portable system this would add significant weight and complexity. Outdoor AR is often used for observing very large area visualizations such as entire buildings or annotations at a distance from the user. Stereoscopic HMDs only emulate some of the depth cues humans use to judge distance, and most of these fail to be effective beyond approximately 30 m [4]. These issues make stereoscopic HMDs not necessary for outdoor use.

Many different mounting systems may be used to attach electronics to user's head. The overall size of the electronics determines the support required from the mounting system. Readily available items such as skate or bike helmets (Fig. 11.4) or safety masks (Fig. 11.5a) can be adapted or modified to be suitable for holding electronic components. Alternatively, custom-designed mounting prototypes can be produced using a 3D printer (shown in Fig. 11.5b). This approach is more expensive but can provide more complex and aesthetically pleasing design that often appeals to those interested in commercial ventures. Figure 11.5c shows a military kevlar helmet modified to include MR hardware.

This figure will be printed in b/w

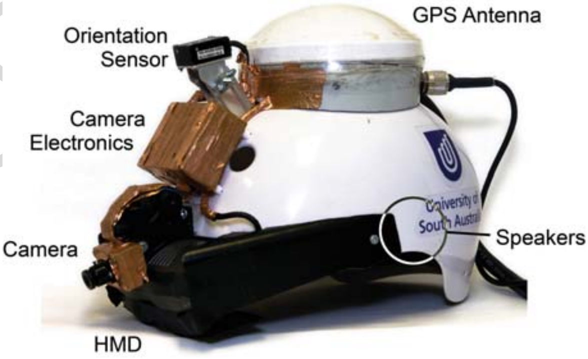
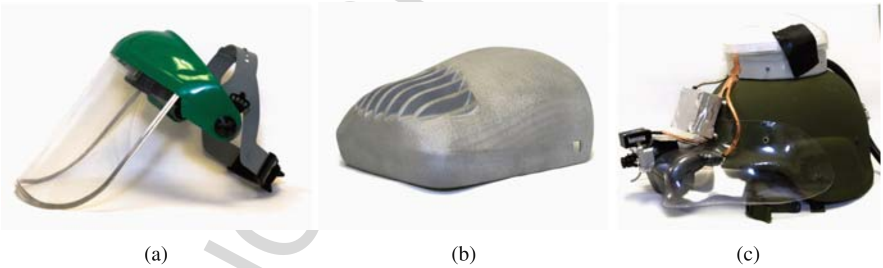


Fig. 11.4 Head-mounted electronics combines an HMD, camera and separate electronics, orientation sensor, GPS antenna, and speakers (internal)

In our 2005 backpack system we attached a Trimble GPS antenna, Intersense InertiaCube3, Point Gray Dragonfly camera, iGlasses HMD, and a number of power regulation circuits to a skate helmet (see Fig. 11.4). Securely mounting the HMD in front of the user's eyes is important to maintain correct. To achieve this we used a commercially available mount developed by iGlasses, with some modifications to finely adjust the mounting location. The camera is mounted as close as possible to the center of the user's eyes to reduce parallax effects. We mounted the camera using a custom mount that enables pitch adjustment to be easily configured for optimal user comfort and functionality. The total weight of the helmet and electronics is 1.5 kg.

More recently as the electronics have become smaller we reduced the overall size of the head-worn electronics. In our 2007 helmet design a head-worn safety shield with the visor removed was used as the main structure for attaching electronics. Although the design is very similar, the overall size and weight have been reduced. Significant size reductions were achieved by employing a smaller GPS antenna.

All of these devices require a communication bus to the computer. The tracking and camera signals are transmitted to the computer, and the appropriate graphics and audio data are computed and sent back to the display and speakers. There are a large number of signal and power wires connecting the head mount and backpack computer. Our current systems require a total of 19 wires: 3 for the orientation sensor, 2 for the antenna, 4 for the camera, 4 for the HMD S-video signal, 1 for HMD power control, 3 for stereo speakers, and 2 for power. One option is to run individual cables to each device. In practice this is inconvenient due to tangles and low flexibility of the cable bundle. We have used a large anti-kink single cable with 8 individually twisted, shielded pairs (contains 8 pairs with individual shields for a total of 24 signal wires). By using an individual large cable, a single plug can also be used to connect the head mount to the main enclosure. This makes the system more robust and easier to rapidly deploy. A LEMO[3] 20-way plug and socket was used allowing quick and reliable disconnection of the head mount and wearable computer.


(a) (b) (c)

This figure will be printed in b/w

Fig. 11.5 Additional types of supports for the head-mounted electronics: (**a**) safety shield; (**b**) custom-designed visor; and (**c**) military kevlar helmet

---

[3] http://www.lemo.com

11.4.2 Main Enclosure

In addition to the head-mount electronics, the user carries a computer capable of generating the graphics. A number of additional support components are required to make a mobile system properly operate, also all carried by the user. We created a single enclosure containing the computer and all supporting peripheral components. By building a single-sealed enclosure there is less risk of components being moved or connectors disconnecting. A major advantage is that each component may be removed from its casing and only the internal electronics be carried allowing a significant reduction in size and weight. The weight of the enclosure and all components is 4 kg. Connections between components and the computer are hardwired reducing the space taken up by connectors. While this approach reduces size and improves robustness, it makes the system more difficult to modify or upgrade. Through a long history of developing outdoor MR systems, we have selected what we feel are the best component choices and found that the size and robustness advantages prevail over the re-configurability restrictions.

The system does still support expansion through the use of external USB, power, and video plugs. Additional devices may be attached to the enclosure and powered by an external 12 V connector on the enclosure. An exposed USB connector allows devices (or hubs) to be connected to the computer as required.

The components included in the main enclosure are as follows:

- Laptop computer
- GPS processor
- Power regulators (12 V, 3.3 V)
- Hard disk drive
- Bluetooth module
- USB hub
- USB/RS-232 converter
- Wireless video transmitter
- Custom microcontroller electronics

A laptop computer is selected instead of an embedded PC given the 3D graphics acceleration requirements that are not available on embedded PCs. We found laptop computers provided the best performance in computation and graphics for the size. When the 2005 system was constructed we used a Toshiba Tecra M2 laptop with a 1.7 GHz Pentium M processor and a NVIDIA Geforce 5200Go graphics card. As there is no need for the keyboard, mouse, or screen on the laptop, the motherboard is extracted from the casing and this alone is mounted in the wearable computer enclosure.

The processor board for the GPS is also installed in the enclosure. We use the Trimble AG132 surveying grade GPS in our 2005 system, capable of differential updates to yield an accuracy of 50 cm. This GPS unit is much larger than those commonly embedded in mobile phones; however, it supports much higher accuracy. This increased accuracy is also achieved by using the large antenna on the head mount. In the 2007 system this unit was changed to the Novatel OEMV-1 which has a much smaller physical size.

Many of the components used in wearable systems have varying power requirements often with different operating voltages. Using a single battery source makes the system much easier to use and maintain compared with separate batteries for each device. The single battery reduces the overhead required to charge the system between uses. Because of these reasons, there needs to be a number of voltage regulators inside the enclosure to provide 3.3 V for our custom microcontrollers, 5 V for the USB devices, and 12 V for the HMD and laptop.

11.4.3 Batteries

With the many required components in a mobile mixed reality system there is a large power requirement. We use a single battery to power the entire system to avoid system failures when one device depletes before the others. Our system uses batteries placed in sealed aluminum enclosures making them very robust and able to be connected to the system with a single connector. The batteries are mounted separately to the main enclosure to allow hot swapping while the system is running supporting an unlimited run-time.

There are many battery technologies available including lead acid (Pb), nickel-metal hydride (NiMH), and a variety of lithium-based technologies, a popular one being lithium polymer (LiPo). We use NiMH and LiPo batteries to power the 2005 and 2007 systems, respectively. These technologies provide good capacity to weight ratios compared with the heavy lead acid battery technology. The NiMH batteries used on the system (shown in Fig. 11.1) supply 12 V with 8000 mAh capacity and weigh 2 kg each. Using a pair of these batteries allows the system to run for approximately 1 h. LiPo batteries are smaller than NiMHs of similar capacity. A disadvantage of LiPo batteries is the additional electronics required for monitoring and charging. The battery enclosures for LiPo batteries need to include load-balancing circuits for charging; however, the increased electrical density reduces the overall size and weight.

11.5 Input Devices

Interacting with a wearable computer is a well-established research problem [17]. The inability to use a regular keyboard or mouse when moving in an outdoor environment creates the need for alternative input devices and associated input metaphors within the mixed reality software. The primary input device we use for interacting with the mixed reality system is the user's hands, in the form of pinch gloves and tracked thumbs (see Fig. 11.6). These gloves control the menu system and direct manipulations as described previously. In addition to the gloves our system supports a button box and toy gun input devices.

11.5.1 Pinch Gloves

Pinch gloves provide the user with an intuitive method of operating menus within the mixed reality system by using simple pinch gestures. Our gloves are constructed using conductive fabric pads on the fingertips and palm and communicate wirelessly via Bluetooth [11]. Pinch gestures are made between the thumb and fingers or fingers and the palm. Attached to the back of the hand is an MSP430 microcontroller circuit. The microcontroller is attached to each of the fabric pads with conductive cotton that is sewn into the interior of the glove. This maintains flexibility of the glove and by hiding the wiring it decreases the chances of wires being caught or broken. The microcontroller detects pinch gestures by pulsing electrical signals to each of the fingers and palm pads looking for open and closed circuits. Attached underneath the circuit is an 850 mAh lithium polymer battery capable of running the gloves continually for over 30 days. The use of wireless technologies and removing the wires that tether the gloves to the rest of the system is important to make the gloves easier to put on and remove and reduce the restriction of the user's movements. Previous mobile mixed reality systems used wired gloves; we found them to be clumsy as the wires running along the arms to the hands easily got caught or tangled.

This figure will be printed in b/w

Fig. 11.6 Wireless pinch gloves allow the operation of menus using pinch gestures. The thumbs are tracked to provide 3D cursors for interaction

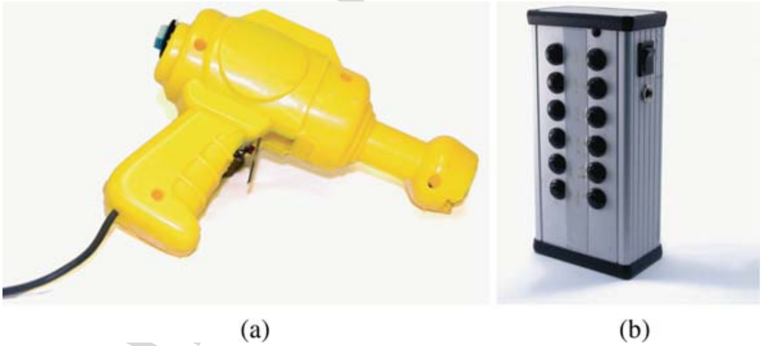
11.5.2 Button Box

The gloves are the primary input device to our system, donning gloves is not always appropriate or possible. We built an alternate handheld input device to emulate the operation of the gloves. We constructed a simple box with 12 push buttons (shown in Fig. 11.7b).

There are a number of advantages to using a button box as an alternative input device for a wearable MR system. By emulating the protocol and operation of the gloves, the user interface can remain consistent across the whole system. This decreases cognitive load for the user when switching between devices. Our button box is robust which is useful when testing the system or when operated by inexperienced users. The button box can be placed on the ground while adjusting the wearable computer with limited chance of breakage unlike pinch gloves. The button box may be used when instructing new users of the system. For example, while the new user is wearing the system the instructor can interact with the interface to demonstrate system operation. The button box can be easily handed between instructor and user. Alternatively the user can wear the gloves while the instructor uses the button box.

11.5.3 Additional Input Devices

Additional input devices may be used with the Tinmith system. We built a toy gun (shown in Fig. 11.7a) for controlling the ARQuake game [19]. The toy gun is based on a child's toy, which has had the internal components of a USB mouse integrated so that the trigger operates the mouse's left-click button. The gun's location is not tracked, but the simple act of pulling a trigger of a physical gun adds a sense of realism when playing the game. Hinkley et al. demonstrated that the use of physical props increases understanding when interacting with a computer compared to using generic input devices [7]. A USB trackpad can be attached to one of the batteries mounted to the belt but is not required to use the system. The system can be completely controlled from a custom manager daemon. This software starts immediately when the system boots and allows a user to use the wireless gloves or button box to perform a number of tasks including starting or terminating software, changing configurations, or setting up wireless networks .


(a) (b)

This figure will be printed in b/w

Fig. 11.7 Additional input devices for mixed reality systems: (**a**) toy gun used with the ARQuake game and (**b**) wireless button box

11.6 Wearable Mixed Reality System Design

In our experience building wearable mixed reality systems, we have used a variety of designs and manufacturing processes. Here we summarize some guidelines specific to these design criteria.

11.6.1 Manufacturing Techniques

We employ computer numerically controlled (CNC) machining equipment to manufacture a variety of the parts required for wearable mixed reality systems. A milling machine uses a rotating cutter to shape metal and plastic parts. A CNC mill is controlled by a computer to quickly and accurately produce parts. We use a CNC mill for the creation of camera enclosures, main enclosure side panels, and cutouts required for connectors and switches. The use of precision machinery allows the components to be smaller and lighter, improving immersion of the MR system. Current 3D printer technologies provide an alternative to the use of a CNC mill for creating plastic parts. Currently cheaper 3D printers produce parts that are too brittle for our requirements. As these devices mature the quality of the parts they produce is improving. While more expensive 3D printers have overcome these limitations they are still not widely accessible. It is expected that as the demand for these devices increases, the cost will be reduced providing a highly accessible and promising manufacturing technique.

AQ4

The PointGrey Firefly MV camera used in our system comes as a circuit board and sensor. We created a compact case for the camera, shown in Fig. 11.8. This allows the camera to be mounted close to the HMD reducing parallax effects. CNC milling is also used to cut out panels for electronics casings. The main enclosure has 17 connectors, switches, and LEDs that are exposed. The use of CNC machining aligns and cuts these very accurately. As seen in Fig. 11.9, connectors are mounted in the side panels, and in addition air vents have been cut to allow sufficient cooling.

This figure will be printed in b/w

Fig. 11.8 A CAD model of a camera enclosure and the CNC-machined final product

This figure will be printed in b/w

Fig. 11.9 Front and back panels of the main enclosure. A variety of connectors are available. Integrated fan grills provide airflow for cooling

We create a 3D design of the desired part in a computer-aided design (CAD) package, and then cut out the model with a CNC milling machine. We use Autodesk Inventor[4] for 3D design and SheetCAM[5] for generating the cutting paths for the CNC mill. The Taig Micromill[6] is controlled using Mach3.[7]

11.6.2 Belt vs. Backpack

In the past the components required for mobile outdoor mixed reality were mounted to a backpack. As can be seen in Fig. 11.2, backpacks can be large and bulky. The combination of components reducing in size as technology improves and our new construction techniques means we have moved away from backpacks. The main enclosure is now small enough to be mounted entirely on a belt. We believe that until computers can be integrated directly into the clothing, or are small enough to be placed in a pocket, that belt worn is a suitable middle ground. A case attached to the belt is easier to conceal behind clothing, and the user can move around more freely. Another benefit to a belt-worn computer is that it is easier for the user to reach behind and manipulate the system as required (e.g., to flip switches or remove plugs).

In our belt-worn system the batteries are attached to the belt using metal clips. The main enclosure is attached using bolts and spacers. Spacers are used to keep

---

[4] http://www.autodesk.com
[5] http://www.sheetcam.com
[6] http://www.taigtools.com
[7] http://www.machsupport.com

the enclosure slightly away from the body. This prevents heat transfer between the body and the enclosure and also improves ergonomics. If the enclosure were to be mounted rigidly to the belt then it would be comfortable against the user's back. The belt is attached to a large 20 cm high padding to make it more comfortable to wear on the waist. One limitation of a belt system is that until the system is extremely lightweight it can be cumbersome to attach and remove from the waist. We employ a military "webbing" belt for the system. Due to the nature of the padding on the belt, these systems have limited adjustability. To fit the range of people who have used our system, different size belts are available.

11.6.3 Electrical and Magnetic Interference

Electrical interference can be problematic when using modified consumer electronics in a confined space. These problems are often amplified when the original cases are removed. Many devices have shielding materials installed on their cases to block signals from both entering and escaping the device electronics. We have followed a number of simple procedures that significantly improved the performance of our wearable systems.

Our MR systems require many signal and power wires to pass through a single cable from the computer system to the head-worn electronics. Placing high-speed USB and firewire signal wires directly next to the GPS antenna cable caused significant tracking reliability problems. The GPS antenna signal was attenuated sufficiently to prevent GPS position lock. To overcome this problem we employ individually shielded twisted pairs for all the signal wires on the main communications cable. Each of the pairs is carefully chosen so the original manufacturer cable design is maintained using our cabling. Additionally, all wire lengths are kept to a minimum and strong solder joints are essential. Grounded copper shielding tape is used extensively both internally and externally on our backpack systems. Copper tape can be purchased with an adhesive backing allowing it to be easily and liberally applied to any questionable interference areas (an example of this can be seen in Fig. 11.4).

11.7 System Management

Engineering the wearable mixed reality system to be smaller and more compact has obvious advantages for mobility and robustness. It causes a number of new issues that are not present with ad hoc systems. These are primarily due to the inability to directly access components such as the laptop screen or individual connectors.

11.7.1 Power Management

With the large number of components embedded in wearable systems and no physical access, there is a need for a dedicated power management system.

A custom microcontroller is responsible for power management, voltage regulation, and software control of device power.

Software power control is needed to allow the user to manually specify when to power devices on and off. When all devices are embedded in the main enclosure, it is not possible to access power buttons or power sockets. For example, software control allows the user to turn the GPS off by selecting an appropriate menu option, without shutting down the entire system. This can also be exploited to save battery life, when certain components are not needed they are powered down, and also for initiating hardware resets of devices during debugging.

Certain devices will not turn on when the power is connected. One example is the IOGlasses HMD, for which the power button needs to be manually pressed to enable it after power is applied. The power management system has a control line attached to the HMD power button, allowing the microcontroller to detect that the system has been booted and automatically turning the HMD on. This makes the system much more automated and removed the need for the user to manually press multiple power buttons when turning the system on.

11.7.2 Configuration Selection

Wearable mixed reality systems operate with a variety of hardware configurations. As our system is currently a prototype, we require a greater number of configuration possibilities; however, even a commercial system would typically require different modes: a regular operation mode, a mode to download data, and a systems maintenance mode. Because there is no access directly to the computer display or input devices, this ultimately needs to be controlled from outside the regular operation of the system. We use a physical thumb-wheel encoder on the side of the main enclose to select from 10 preset configurations that are loaded when the system is booted. Using an external monitor and keyboard is an example of why this approach is required. If the system is taken outdoors and booted while configured to use an external monitor, nothing is output to the HMD. The system would be unusable and the user would have no display to alter the setup with. Making the user return to an external display to reconfigure the system is unrealistic. With our technique, the user can simply select the appropriate mode with the rotary dial and reboot the system.

Our technique uses a physical rotary encoder with selections 0–9. This component is monitored by the power management circuit. When the system is booted, the power management system reads the configuration selection and communicates the value to the operating system via the RS-232 serial connection. We have created a custom Linux boot script that is run early during the boot process that reads the device number from the power management unit and changes configuration files on the system accordingly.

Different configuration options we use include combinations of video output (VGA monitor vs. HMD), wireless networks, Bluetooth scanning modes, and different softwares loaded at startup.

11.7.3 Input Management

The glove and button-box input devices operate wirelessly using Bluetooth. Bluetooth is a suitable wireless standard for input devices due to relatively low power consumption, short range, small size of the hardware components, and ease of integration with existing software. A single USB-based Bluetooth receiver is capable of being shared to communicate with multiple devices. Modern operating systems such as Linux include support for communicating with Bluetooth devices. In the external hardware devices, we use Promi-ESD-02 Bluetooth modules,[8] prepackaged Bluetooth wireless solution that is easily interfaced with existing and new circuit designs. They are small (20 mm × 18 mm), reliable, and come with a number of different antenna configurations depending on the range required. These modules support the RFCOMM standard, which is a simple interface allowing RS-232 communications over Bluetooth. On the PC end, no actual serial ports are needed, except for the interface provided by the single USB Bluetooth receiver.

To communicate with the devices in software, applications can open virtual serial ports or use RFCOMM directly via a Berkley Software Distribution sockets interface. The virtual serial port interface is a high-level abstraction, which limits its ability to indicate timeouts, wireless failures, or remote device failure. The direct RFCOMM interface allows finer-grained control over the device communications, allowing reconnects and other handling when necessary. Scanning for all RFCOMM devices and connecting is time consuming, and so typically the backpack system is pre-configured to maintain a list of active devices. To connect to new devices, the rotary encoder is dialed into Bluetooth scanning mode, the backpack then polls for devices, and records a list of those available. This way, if other devices are present or possibly paired up against other MR systems, there will be no conflict.

While Bluetooth has demonstrated itself to be reliable, it is mainly used for portable and optional input devices. These devices have low bandwidth requirements, and having cables would make them harder to use. System critical devices such as the rotary encoder must not be wireless, so that it can be used to configure the wireless system.

11.7.4 External Display

On our earlier backpack hardware systems, the laptop's screen was left open allowing people observing to see what the user of the system is experiencing (Fig. 11.2; 2001, 2002, 2004). This allowed us to perform demonstrations to a large audience using only one backpack system. This proved to be compelling and interactive for the observers; however, with the laptop attached to their back the user's movements became restricted. For example, when the user turns around the entire audience would shuffle around quickly to maintain a good view of the laptop's screen. To

---

[8] http://www.sena.com

overcome this problem, we have built an external display that is used to view what is currently being displayed on the HMD. This operates in one of two modes, wirelessly or via a cable. The HMD receives a PAL S-Video signal generated from the TV-Out of the integrated computer. A 1.2 GHz video transmitter is built into the main enclosure and connected to the S-Video signal using component-converting electronics. This transmits the video to our external display. The external display contains an LCD panel, battery, and video receiver. The display is shown in Fig. 11.10.

The external display can also be directly wired to the main enclosure with an RCA connector. The physical wired connection to the main enclosure is particularly useful to allow recording of videos of the system in operation. A handheld video camera is connected directly to the main enclosure and records a copy of the signal sent to the HMD. This allows videos to be recorded without interfering with the user's ability to operate the system.

The external display has a number of important uses. The first is for debugging the system. The HMD displays are small and although they operate at the same resolution as the external display, it can be difficult to read small text on the HMD. The external display is used if commands have to be manually entered into a Linux terminal. The other important use of an external display is when operating the system with other users. Those people not using the system are able to see what the operator is viewing. This is invaluable when training a new user, as the instructor can see exactly what they are viewing and instruct them accordingly. Similarly,

This figure will be printed in b/w

Fig. 11.10 External display containing an LCD panel and an integrated battery and wireless video receiver when an expert user is operating the system, the display can be shown to other people for demonstrations or training. This display is often used when performing user evaluations to instruct and monitor study participants.

11.8 Conclusion

Developing mobile mixed reality systems requires unique interaction techniques and hardware systems. We have presented how interaction techniques and the mobile requirements of outdoor MR systems have directed the development of the hardware systems. Considerations such as user comfort, configurability, robustness have all contributed to the evolution of mobile mixed reality systems built over the last 10 years.

We have developed portable MR hardware systems and user interfaces that we found in practice to be significantly easier to use and more reliable than the previous bulky backpack designs. As the technology improves we will continue to refine and improve our design, aiming toward the goal of a completely immersive and ubiquitous system that a user wears and interacts with at all times. Our current system has many limitations that we are still investigating. These limitations are mainly based on the current state of the art in common off-the-shelf hardware components. While HMDs with a larger field of view are available, they are very bulky and not suitable for use outdoors. GPS devices can achieve accuracy to around 2 cm; however, this requires optimal conditions in an unobstructed environment – they do not work well under foliage, among buildings, on cloudy days and especially indoors. The overall system is still based on OEM components, which limits the overall size that is possible. The optimal solution is to design a single PCB with all of the components integrated. This is possible with large budgets and large quantities, something which is not practical in a research field like mixed reality yet.

Consideration needs to be made about the devices needed to create a mixed reality. Some components must be mounted directly on the user's head, but these components also need to communicate and be powered from the rest of the electronics. The size of the required components is no longer such that bulky backpacks need to be used as has been done in the past, but they are not yet small enough to be simply placed in a pocket. We used a belt-mounted design as a current middle ground, allowing the user to wear the system comfortably around the waist. The research described in this chapter is a work in progress that has evolved over many years, and we are continuing in our efforts to achieve improved performance and usability while at the same time reducing size and weight of our MR systems.

References

1. Azuma, R. T. The challenge of making augmented reality work outdoors. In *Mixed Reality: Merging Real and Virtual Worlds*, Ohta, Y. and Tamura, H., Editors, Springer-Verlag, Berlin, pp. 379–390, 1997.

2. Baillot, Y., Brown, D. and Julier, S. Authoring of physical models using mobile computers. In *5th Int'l Symposium on Wearable Computers*. pp. 39–46. Zurich, Switzerland 2001.
3. Behringer, R., Tam, C., McGee, J., Sundareswaran, S. and Vassiliou, M. A wearable augmented reality testbed for navigation and control, built solely with commercial-off-the-shelf (COTS) Hardware. In *3rd Int'l Symposium on Augmented Reality*. pp. 12–19. Munich, Germany 2000.
4. Cutting, J. and Vishton, P. Perceiving layout and knowing distances: The Integration, relative potency, and contextual use of different information about depth. In *Handbook of Perception and Cognition*, Epstein, W. and Rogers, S., Editors, Academic Press: San Diego, CA. pp. 69–117. 1995.
5. Feiner, S., MacIntyre, B. and Hollerer, T. A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. In *1st Int'l Symposium on Wearable Computers*. pp. 74–81. Cambridge, MA 1997.
6. Guiard, Y. Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. Journal of Motor Behavior, 1987, 19(4) pp. 486–517.
7. Hinckley, K., Tullio, J., Pausch, R., Proffitt, D. and Kassell, N. Usability analysis of 3D rotation techniques. In *10th Int'l Symposium on User Interface Software Technology*. pp. 1–10. Banff, Canada 1997.
8. Hollerer, T., Feiner, S. and Pavlik, J. Situated documentaries: Embedding multimedia presentations in the real world. In *3rd Int'l Symposium on Wearable Computers*. pp. 79–86. San Francisco, Ca 1999.
9. Julier, S., Lanzagorta, M., Baillot, Y., Rosenblum, L., Feiner, S. and Hollerer, T. Information filtering for mobile augmented reality. In *3rd Int'l Symposium on Augmented Reality*. pp. 1–10. Munich, Germany 2000.
10. Lehikoinen, J. and Röykkee, M.. N-fingers: A finger-based interaction technique for wearable computers. Interacting with Computers, 2001, 13(5) pp. 601–625.
11. Piekarski, W. and Smith, R. Robust gloves For 3D interaction in mobile outdoor AR environments. In *5th Int'l Symposium on Mixed and Augmented Reality*. pp. 251–252. Santa Barbara, USA 2006.
12. Piekarski, W., Smith, R. and Thomas, B. Designing backpacks for high fidelity mobile outdoor augmented reality. In *3rd Int'l Symposium on Mixed and Augmented Reality*. pp. 280–281. Arlington, VA, USA 2004.
13. Piekarski, W. and Thomas, B. Interactive augmented reality techniques for construction at a distance of 3D geometry. In *Immersive Projection Technology/Eurographics Virtual Environments*. pp. 19–28, Zurich, Switzerland 2003.
14. Piekarski, W. and Thomas, B. The tinmith system – Demonstrating new techniques for mobile augmented reality modelling. In *3rd Australasian User Interfaces Conference*. pp. 61–70. Melbourne, Vic 2002.
15. Reitmayr, G. and Drummond, T. W. Going out: Robust model-based tracking for outdoor augmented reality. In *5th Int'l Symposium on Mixed and Augmented Reality*. pp. 109–118. Santa Barbara, USA 2006.
16. Schmalstieg, D. and Wagner, D. Experiences with handheld augmented reality. In *6th Int'l Symposium on Mixed and Augmented Reality*. pp. 3–18. Nara, Japan 2007.
17. Starner, T. and Rhodes, B.. Wearable computers. In *Encyclopedia of Human-Computer Interaction*, Bainbridge, W., Editor, Berkshire Publishing: Great Barrington, MA 2004.
18. Suomela, R. and Lehikoinen, J. Context compass. In *4th Int'l Symposium on Wearable Computers*. pp. 147–154. Atlanta, GA 2000.
19. Thomas, B., Close, B., Donoghue, J., Squires, J., De Bondi, P., Morris, M. and Piekarski, W. ARQuake: An outdoor/indoor augmented reality first person application. In *4th Int'l Symposium on Wearable Computers*. pp. 139–146. Atlanta, GA 2000.
20. Thomas, B. H., Demczuk, V., Piekarski, W., Hepworth, D. and Gunther, B. A wearable computer system with augmented reality to support terrestrial navigation. In *2nd Int'l Symposium on Wearable Computers*. pp. 168–171. Pittsburg, PA 1998.

Chapter 11

Q. No.	Query
AQ1	We have inserted citation of Figure 11.1 to maintain figure sequential order. Is this Ok?
AQ2	The printed version of the book is in gray-scale format. Please rephrase the text of Fig. 11.3 without the mention of colors.
AQ3	The text “Erreur! Signet non défini.” is given. Please update the citation.
AQ4	The text “Erreur ! Source du renvoi introuvable.” is given. Please update the citation.