A Wearable Augmented Reality Testbed for Navigation and Control, Built Solely with Commercial-Off-The-Shelf (COTS) Hardware

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Abstract

Personal applications employing Augmented Reality (AR) technology for information systems require ease of use and wearability. Progress in hardware miniaturization is enabling the development of wearable testbeds for such applications, providing sufficient computing power for the demanding AR tasks. RSC has assembled a wearable testbed for AR applications, comprising only of commercial off-the-shelf (COTS) hardware components. The system is designed to be worn like a jacket, with all hardware attached to a vest frame (Xybernaut) with concealed routing of cables under Velcro channels. Two possible configurations allow the system to be used either in a stand-alone mode ("itWARNS") or to be linked to a larger scale multi-modal user interface testbed ("WIMMIS"). Completely tetherless operation is made possible by wireless digital connections, as well as analog video and 3D audio connections over radio frequencies (RF). This paper describes these two testbed configurations, as well as some of the AR applications, developed on this testbed.

1. Introduction

To develop personalized applications of Augmented Reality (AR), which are built around head-worn displays (HWD), wearable testbeds are needed to allow simulation of the possible user interactions with such an AR system, so that the user is not tethered and can move freely in the "augmented" environment. Practical experiences (e.g., the Boeing pilot project [6]) stress the need for lightweight and powerful wearable testbeds. Advancements in hardware miniaturization (e.g., Pratt's matchbox PC *TIQIT* [7]) have now enabled the setup of wearable computing systems that provide the necessary computing power for the demanding tasks in AR applications, although their applicability in real world applications may still be a bit away. In most existing wearable AR testbeds, a backpack system is used to carry a computer and accessories (e.g. [8], [12], [15]). Newer systems can make use of the smaller form factor of wearable computers that can be worn on a belt (e.g. Xybernaut® [16], VIA® [14]).

In order to provide a testbed for the AR applications, developed at Rockwell Science Center (RSC), we have used commercial off-the-shelf (COTS) components (Xybernaut® PC and a vest) to assemble a wearable computing system. RSC AR applications include maintenance using "X-Ray vision" [5], integrated multi-modal command centers [13], and possible simulations for future flight displays [4].

In this paper, we describe this testbed and the COTS components. We also discuss the design choices made and provide a glimpse of the AR demonstrator applications being developed on this testbed.

2. Hardware for wearable testbeds

2.1. The RSC setup

For developing tetherless AR applications, we needed a wearable testbed, which was light enough to be worn for a while without fatigue, but was powerful enough to be used for AR. The user has a few choices for assembling such a testbed, depending on the specific requirements. The choices we made were based on the commercially available hardware and are kind of a compromise between satisfying these requirements and providing standardized hardware modules which can be easily replaced in case of failure.

The computing power in our system is provided by a Xybernaut® MA-IV (233 MHz Pentium CPU). In the current setup, we are using a vest from Xybernaut® to mount the accessory hardware (RF receivers resp. transmitters). Although this vest is still far from the "smart clothing" envisioned by Steve Mann [11], it is a first step towards easy handling of a wearable information system. The vest is easy to put on, like a jacket. Everything is wired within the vest, and the user does not have to worry about plugging in connectors. The total weight of the vest is under 16 lbs, with significant weight contribution from the batteries. The weight, however, is evenly distributed by the vest. Figure 1 shows the vest and the mounted hardware.

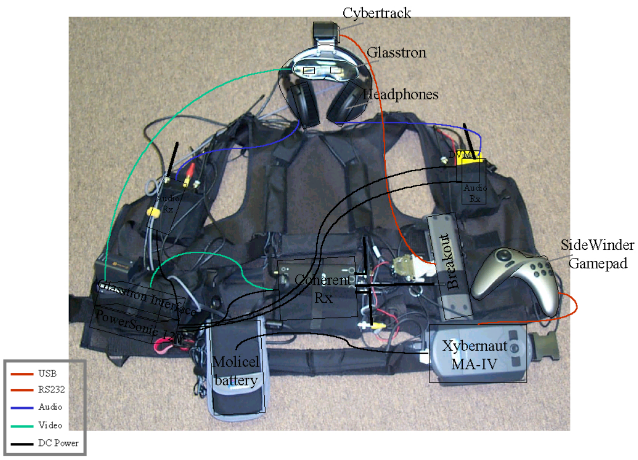

Figure 1. The wearable vest with hardware and connections.

Besides the Xybernaut computer, the vest includes the following hardware:

- Full Xybernaut® port replicator.
- Sony Glasstron® PLM-S700 head-worn binocular display for AR overlay.
- CyberTrack II head tracker for sourceless head orientation tracking.
- Coherent CVR-1500 wireless audio/video receiver for video and monaural audio RF reception.
- Two AudioTechnica audio receivers ATW-R100 for stereo (3D) audio reception.

The system is running Windows98® for easy portability and software development environment. Although this may not be viewed as the ultimate answer for future wearable systems (see discussion in [9]), it provides a (relatively) stable environment with many available drivers for a large variety of hardware. We have implemented two "flavors" of this testbed:

- "itWARNS" (Intelligent Tetherless Wearable Augmented Reality Navigation System): a stand-alone system which generates the display content locally on the wearable computer itself. It can optionally be connected to a computer network to send and receive data, but can also operate completely autonomously to show locally stored information.
- "WIMMIS" (Wearable Immersive Multi-Media Information System): a system integrated into a computer network, with externally generated display content. Video and stereo audio are received through analog RF transmission channels.

Both systems (WIMMIS always, itWARNS optional) are connected to the LAN via a Proxim® RangeLan2 wireless Ethernet, which provides up to 1.6 Mbit bandwidth. The communication protocol is implemented using TCP sockets. Wireless connectivity ensures completely tetherless operation of the wearable testbed.

In the following sections, we describe the hardware choices made for this wearable testbed and discuss the benefits and the possible tradeoffs.

2.2. Wearable PCs

The two wearable PCs we have tested are the Xybernaut MA-IV and the VIA II. The recently available TIQIT matchbox PC by Vaughan Pratt [7] was not considered by us, because it provides just the capabilities of a 486SX CPU, running with 66MHz. This is not sufficient for the anticipated multimedia capabilities of our applications, but it may be sufficient for specific applications, where no complex display or communication capabilities are required. We also did not consider other light-weight PCs, like the "Plug-N-Run" from Cell Computing or the "Espresso PC" from Saint-Song, which may be good alternatives to Via and MA-IV in terms of weight and processing power, but are not specifically targeted towards wearability and therefore would require certain customizations.

Table 1. Comparison of the "wearable computers" Xybernaut® and VIA®

	Xybernaut MA-IV	VIA II
Processor	233 MHz Pentium MMX	166 MHz Cyrix MediaGX
Memory		64 MB DRAM
Display	monocular head-worn LCD, also VGA out	handheld tablet touch panel
Size	18.7cm × 6.3cm × 11.7cm	24.8cm × 7.9cm × 3.2cm
Weight (no battery)	900g	780g
Port replicator	relatively small	heavy (for desktop)
Battery	single	dual (hot swappable)
Pros	Sufficient computing power and connectivity	small form factor light weight
Cons	Bulky form factor	limited computing power, limited connectivity

The comparison of our two wearable PCs in Table 1 includes technical data, as well as pros and cons, for our specific applications. It can be seen that the "flexible PC"

VIA® beats Xybernaut® in size, form factor, and weight. Also, the VIA has a hot-swappable battery cable. However, it does not currently provide sufficient connectivity to the numerous accessories in our system. For example, without the stationary base station, no standard VGA display could be connected directly to the VIA® (important for debugging and for using the Sony Glasstron). We also had problems connecting a Socket® dual serial port PC card to the system. In spite of the shortcomings, we plan to build another wearable system centered around the VIA® to take advantage of VIA's attractive physical flexibility and slim form factor. Both manufacturers recently announced improved and upgraded versions of their wearable PCs, up to 600 MHz clock. We will continue to monitor the market for future upgrades to our existing testbed.

2.3. Tracking head orientation: CyberTrack®

For providing correctly aligned visual information on a head-worn display, head orientation must be tracked continuously. Since the wearable testbed is supposed to be used also in an outdoor environment, the head tracking should not rely on external tracking systems which would only function in a confined area and require external infrastructure. For instance, magnetic tracking would involve a transmitter and would function only within the range of the transmitter. Therefore, we use a sourceless magnetometer (digital compass), CyberTrack®, as the main head tracking device. It is mounted on a set of headphones, as seen in Figure 2 and in both pictures of Figure 4.

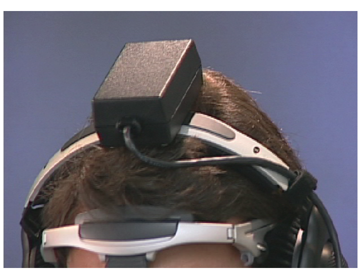

Figure 2. CyberTrack head orientation tracker, mounted on Sennheiser headphones.

Combined with a built-in inclinometer, this device provides yaw, pitch, and roll angle. The precision is not overwhelming (yaw: $\pm 5^{\circ}$, pitch and roll $\pm 1^{\circ}$), but is acceptable for rough orientation and initialization. However, it is possible that a larger error appears in some outdoor locations [1]. In this case, an additional tracking system must provide more precise calibration, for example by a gyro. Currently, we do not have any additional tracking system installed. We plan, however, to implement an Intersense® sourceless tracker to achieve improved accuracy and decreased latency. The reason why we currently do not use the Intersense® tracker, is because it requires an additional interface box to be carried. The Xybernaut head set provides the means for attaching a camera (next to the left eye in Figure 4, right picture) for video capture (640x480 color). The video will either be captured locally and transmitted over socket IP or be broadcast using analog RF and captured on a remote computer. This will allow us to test real-time video-based registration algorithms in order to improve the head tracking precision, as described in [3]. Work needs to be done to make that approach real-time executable. But the camera can also be used to simply broadcast the user's view to a stationary base station. We have reinforced the camera mounting to provide a more rigid orientation fixation (Figure 3).

Figure 3. Retrofit Xybernaut camera for more stable orientation fixation.

2.4. User location: GPS module

We have developed a Portable GPS Control (PGC), an ActiveX control designed to provide convenient and portable functionality to developers who wish to add Global Positioning System (GPS) support to a software application. The PGC can be embedded into any ActiveX container or can be integrated into a Visual Basic or Visual C++ development project with minimal effort. It provides simple and automatic communication, through a serial port, with most commercial GPS receivers that feature serial data output. By conforming to the National Maritime Electronics Association Standard #0183 (NMEA-0183), the PGC is able to interpret transmitted data from a wide range of devices, notably those produced by the *Magellan* and *Garmin* corporations, which manufacture the most popular and widely available commercial GPS receivers.

The features of the PGC include convenient user access to communication port settings at runtime, visual indication of connection status, and optional real-time display of raw NMEA-0183 data. The PGC also offers real-time visual display of latitude, longitude, altitude, and velocity of the system, UTC, status of each satellite, and quality of the GPS fix. Additionally, and perhaps most significantly, the PGC exposes methods whereby an encapsulating application can query for any available GPS datum, NMEA-0183 sentences, communication information, data acquisition statistics, or an encoded representation of all available GPS data. In the case of this final option, a C++ function and corresponding structure definition are provided to decode the data into a more usable form for the application.

2.5. Head-worn displays

Two head-worn displays can be connected to the wearable system:

- The monocular color display (640x480), shipped with the Xybernaut, is manufactured by Kopin (Figure 4 right). It has two interchangeable mirrors: either completely opaque for blocking display, or semi-transparent for AR overlay.
- Any VGA compatible display can be connected through an external adaptor. We use a SONY Glasstron PLM-S700 (Figure 4 left), which has a resolution of 800x600 pixels and a variable opacity for controllable see-through capability.

Figure 4. Head-worn displays: left: SONY Glasstron display with headphones and Cybertrack on top. Right: Monocular display and head set from Xybernaut. A camera is attached on the left head side.

Both displays have their merit for different applications. The SONY Glasstron provides a higher resolution, a more immersed feeling, and a more attractive form-factor, whereas the Kopin solution does not block any viewing area. However, the mirror of the monocular Kopin display is very fragile and not suited for real workplace environments. Neither display is suitable for use in bright outdoor situations, as their contrast is too low for application in normal sunlight, but the variable opacity of the SONY display permits the use in a brighter environment than the Kopin display. Future systems may use a Microvision® retinal display, which promises outdoor usability even in bright sunlight.

Neither of the displays has a binocular stereo capability. SONY has discontinued the production of the Glasstron which had that capability. However, stereo video is only necessary for applications which display objects in close range. Our applications, however, are targeted towards displaying objects which are in a far distance from the user.

2.6. Connectivity

The wearable computer is connected to the LAN by a Proxim® RangeLan2 PC card. This provides a theoretical bandwidth of 1.6 Mbit/s; however a more realistic throughput was measured to be around 400 Mbit/s. This is sufficient to upstream small datasets with video frame rate (30 Hz). It also is sufficient for down-streaming information which can be displayed on the display overlay. The rapid development in the area of wireless connectivity (e.g., IBM's Bluetooth) will eventually provide higher bandwidth for a larger amount of data communication.

In order to provide a sophisticated 3D rendition, which is not possible to generate on the Xybernaut itself, we used the SONY Glasstron in the video display mode and transmitted a video image of a 3D rendition to the wearable system (see next chapter "WIMMIS"). We used a Coherent CVR-1500 wireless audio/video receiver with triple diversity antennas for receiving analog video, sent from a corresponding base station Coherent CVT-1400. The antennas connected to the triple diversity receiver are mounted on the front and back of the vest to ensure signal reception, independent of the user's orientation. The signal reception quality depends strongly upon the surroundings. The specified outdoor range is given as 100m. We had placed the transmitter antenna indoors behind a glass wall and could receive the signal from a distance of up to 50m. In an indoor environment, we could travel up to 30 m before the reception began to fade.

This video transmission also allows monaural audio to be sent. However, we needed a 3D audio reception for our system, and therefore had to install an additional RF link. In order to have two audio channels with identical high-quality frequency characteristics, we use two Audio-Technica® ATW-R100 double diversity receivers.

3. Software implementations on the testbed

3.1. Stand-alone system "itWARNS"

One of the two implementations of the wearable testbed is the "Intelligent Tetherless Wearable Augmented Reality Navigation System" (itWARNS). This system is a further development of a previous AR system, which was based on overlay onto live video. Currently, this system does not have much "intelligence" built in, nor does it actually warn. However, it will be able to provide context- and location-sensitive visual information for navigation, and it will be further developed to provide warnings of possible hazards in the context of the user's mission. The current implementation of itWARNS provides the following visual cues (see Figures 5 and 6):

- Artificial horizon;
- Vertical gravity axis;
- Cardinal directions;
- Pitch and roll angle;
- Horizon silhouettes;
- Labels of relevant topographical features.

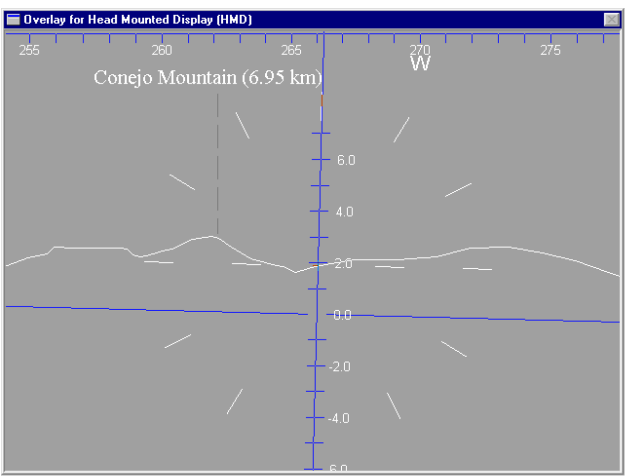

Figure 5. Display content of itWARNS for see-through application. The background is actually black, but is set to gray here for better readability in this print.

The horizon silhouette is currently being calculated offline for given locations. Based on the GPS input, the appropriate silhouette is shown in the display. The background is black, which in a see-through display allows the real world to be viewed by the user (Figure 5). This system can be used as a low-cost simulator of cockpit HUD systems [4]. The itWARNS system can use either the Kopin or the SONY display. In Figure 6 the overlay is shown as seen on the SONY Glasstron. The view is towards the hilly terrain in Thousand Oaks near the RSC facilities.

Figure 6. Overlay of itWARNS as seen on one of the oculars of the SONY see-through display.

3.2. Integrated system "WIMMIS"

In a project on advanced and interactive displays, we have developed a multi-modal display testbed for demonstrating and experimenting with Human Computer Interaction (HCI) input and output modalities [13]. This testbed incorporates visualization and auralization of sensor data, 3D terrain data, and observation and control of a sensor network. Speech recognition and a variety of other interactions are used to interact with this system. The testbed hosts a variety of displays including handheld PCs, wearable PCs, desktop displays, and a 12ft-diagonal back-projection screen. In this context, the wearable computing platform is used to provide an immersive view of the 3D terrain from any given point. This "Wearable Immersive Multi-Media Information System" (WIMMIS) acts as a server, wirelessly providing head orientation data to the multi-modal display testbed with a data rate up to 25 Hz. Also, a game pad can be used to control the viewpoint and display modes. In Figure 7, the projection of the 3D terrain is shown on the large screen, while the WIMMIS user is wearing the vest and controls the viewpoint. On the HMD, the same view is shown as on the large screen.

The 3D terrain rendering program "ARscape", developed by us specifically for this multi-modal display testbed, is based on 1 arc sec. (approx. 30m) resolution National Elevation Data (NED) from the area around RSC. The terrain database was created using the TerraVista® software from TerreX®. Aerial photographs and topographic contour maps from USGS were used for the terrain skin's texture. Figure 7 shows a screen-shot of the

3D terrain visualization of this dataset. ARscape is a Microsoft® Visual C++ application built using the VTree® API from CG2® for rendering. VTree is a platform independent (NT or UNIX) 3D graphics toolkit built on OpenGL ®. It also supports the TerraPage® fast database paging format output by TerraVista®. The ARscape system is implemented on an SGI 320 NT workstation.

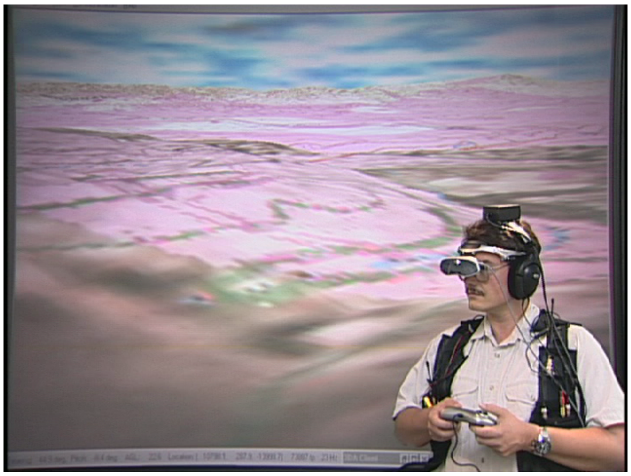

Figure 7. Integration of ARscape and WIMMIS.

The rendered 3D terrain view is converted into NTSC and sent via analog RF transmission to WIMMIS. The receiver is a Coherent® diversity receiver, which allows enhanced signal reception independent of the user's orientation. The antennas are integrated in the wearable vest to allow reception from various user orientations. In addition, 3D audio, generated by a 3D audio server using an Aureal® chipset with hardware head-related transfer functions (HRTF), is also transmitted to the user via analog RF. This allows the user to be alerted about threats that are not currently in the field of view.

WIMMIS is currently used in a fully immersive mode, with texture mapping and shaded rendering enabled (Figure 8, top). However, by changing the rendering mode from fully rendered to wire-frame rendering with black background, the system has the capability of being expanded to a true AR system, with only the most relevant 3D information rendered onto the real view of the terrain. By setting the rendition mode to produce fog and to remove the texture and lighting, the terrain can be shown only as gray objects, with the degree of gray varying with the distance (Figure 8, middle). This can be used to highlight terrain silhouettes in a see-through display, applied in the real environment. Carried to the extreme, where no fog is enabled and the rendition is set only to render black/white, the displayed image is highlighting only the horizon silhouette at the transition from the black terrain to the white sky (Figure 8, bottom).

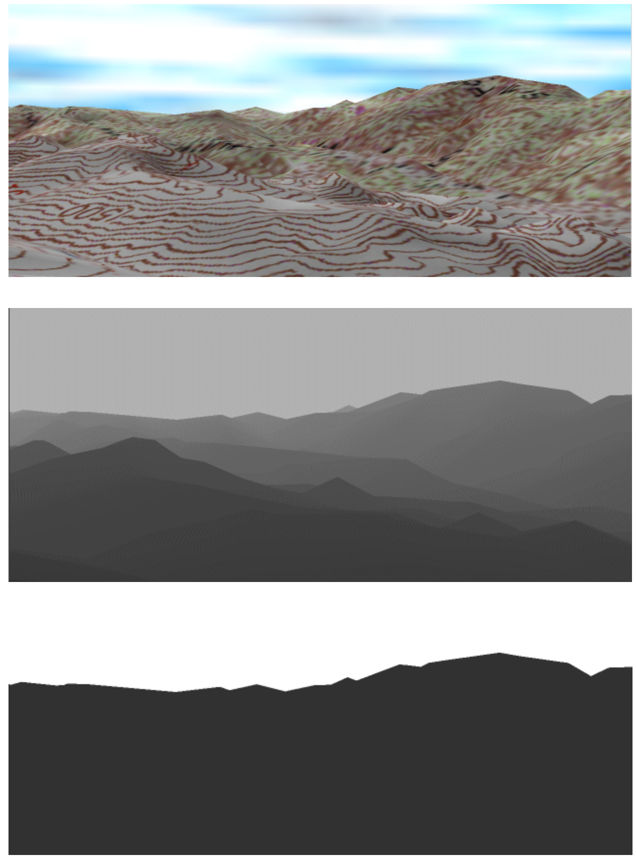

Figure 8. Top: fully illuminated 3D terrain rendition. Middle: fog mode produces set of contour horizons. Bottom: rendition shows only horizon silhouette.

4. Usability issues

We have not conducted formal studies regarding the usability of this wearable testbed. However, we would like to share our daily experiences with this system.

4.1. Battery life

A long battery life is one of the prime requirements for using a wearable system in real-life applications. For demonstrations and development, however, limited battery life may be tolerated to some extend, and current technology allows a decent time for continuous operation of the wearable system. If a bank of reserve batteries are kept, one can ensure that experiments will not be interrupted by the process of recharging. The wearable vest uses a set of three batteries to power the different devices, providing a total capacity of 106 Wh, weighing 1750 g. Depending on the configuration, only a subset of these batteries is actually used.

The Xybernaut PC is powered by a Molicel Li-Ion cell ME202BB (11.1 V, capacity 4.5 Ah) which can provide power realistically for two hours (without any power savings features on the PC enabled). If instead of the Xybernaut display, the SONY Glasstron is used (which uses its own battery), the up-time is increased to three hours.

The SONY Glasstron display is powered by its own Li-Ion battery NP-F950, which provides 32.4 Wh and a voltage of 7.2V (4.5 Ah). No data is available on the power consumption of the Glasstron display, but we can operate it continuously for at least two hours. The consumer version of this display, which we are using, has the following annoying habit: for safety reason, it switches off after 2 hours of continuous use and has to be powered up again. This interrupts the operation of the system after two hours. However,this time can be used for a general battery change.

A separate 12V battery (Powersonic A18180-1 lead accu) with standardized connectors for any 12V input provides a power of 2 Ah for the auxiliary devices on the wearable system. This battery can power the head tracker for eight hours, if no other devices are connected. WIMMIS requires more power for the additional video and audio receivers, which are also powered by this 12V battery. The additional consumption reduces the battery life from eight to two hours. A voltmeter, integrated into the vest circuits, provides a low battery warning when the voltage level drops below 12 V. In Table 2 the power consumption of the devices in this circuit is shown. Although the ratio of power vs. weight is the worst for this battery, it is quite useful because it provides non-proprietary connectors for additional auxiliary equipment.

Table 2. Power consumption in the 12V circuit

	Current at 12V
CyberTrack	250 mA
Coherent CVR-1500	330 mA
2 × AudioTechnica	400 mA
Total Σ	**980 mA**

4.2. Wearability

No formal studies have been conducted at RSC with the wearable vest. However, heuristic user feedback during a demonstration at a Symposium [2] in March 2000, where WIMMIS was tried by over 40 people (about 10 minutes for each trial), was very positive. The relatively even weight distribution of the vest makes carrying the 7.0 kg (<16 lbs) equipment bearable. Table 3 gives a listing of the weight of each device in the wearable testbed. The total weight on the user's head is 560g, which is acceptable even for wearing during a longer period of time.

Table 3. Weight of the wearable components

	Weight
Xybernaut	900g
docking station	300g
Coherent CVR-1500	650g
2 × AudioTechnica	900g
Sennheiser headphones	200g
Cybertrack head tracker	180g
SONY Glasstron head-worn display	180g
Glasstron base	300g
Lead battery	1000g
Sony battery	300g
Molicel battery	450g
Vest with holsters	1200g
Cables and connectors	450g
Total	**7.0 kg**

5. Future AR projects – work in progress

In order to demonstrate the progress of development and integration of AR technology, RSC is developing a demonstrator for navigation, built on the wearable testbed "itWARNS". The system will be targeted towards indoor navigation in one of the office buildings of RSC and will allow a user to find his way around by displaying directional cues and room numbers, projected into the user's view. Registration will be based on head orientation from the CyberTrack and on positional updates from the visual ring marker detection system, employed in a previous RSC AR demonstrator [5]. The HWD could be either the Sony Glasstron or the monocular Kopin display. The 3D framework will be modeled using Direct3D, since the wearable computing platform does not provide an OpenGL accelerated graphics hardware. Using Direct3D here provides a slight speed advantage vs. software-based OpenGL emulation. When the user moves his head down and looks down towards the floor, a 2D floor map will be displayed, correctly aligned with the orientation of his environment.

6. Summary and conclusions

We have assembled a wearable computing system to be used as a testbed for various AR applications. The capability of such wearable platforms is beginning to meet the requirements of AR systems. Future hardware improvements will contribute to better usability, reduced weight, and prolonged battery life. This will benefit the AR applications to be developed with this testbed. Our focus for future work is on enhancing the capabilities of these AR systems, especially in the areas of registration, communication, and networking.

7. Acknowledgements

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