MIThril: context-aware computing for daily life

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Abstract

MIThril is a functional, operational body-worn computing architecture for context-aware human-computer interaction research and general-purpose wearable computing applications. It is ergonomic, flexible, and designed to be integrated into ordinary street clothing. The MIThril architecture combines a multi-protocol body bus and body network, integrating a range of sensors, interfaces, and computing cores. At the time of this writing, it has been in development for over a year and continually refined through daily use for the last seven months. MIThril is an open-source hardware/software platform initiative designed to foster collaboration among researchers and focus attention on the last frontier of wearable computing: daily life.

1 Introduction

Wearable computing research has traditionally been associated with bulky gear, geeky researchers, and military or industrial applications. Such associations are not unwarranted; prototype hardware and specialized applications far removed from ordinary experience are the norm. However, the last five years has seen an explosion in popularity of portable digital applications for every-day use, such as cell phones and PDAs. For our work to be relevant, we must turn our attention to the applications and problems of daily life.

1.1 Applications for Daily Life

The growing popularity of portable consumer electronic devices for communications (cell phones and pagers), logistics and memory (PDAs), shopping (smart cards), athletic performance monitoring, *etc.* demonstrates the demand for technological solutions for the problems of daily life. These applications are usually packaged as separate devices, with little concern for integration, interoperability, or competing demands for the user's attention.

We believe that the promise of wearable computing is an always on, always available information resource; an integrated multi-application framework that consolidates processing power, mass storage, wireless networking, and user interaction, while balancing demands on the user's time and attention. The wearable should be an invisible, reliable assistant or *aid-de-camp* that understands the user's task, goals, and preferences, and uses this knowledge to provide assistance when necessary and otherwise stay out of the way.

In order to realize this vision, the wearable must be highly accessible yet unobtrusive, able to interrupt the user but careful to do so only under appropriate circumstances. The interface must maximize the value of the information provided while minimizing the physical and cognitive burdens imposed by accessing it.

1.2 The Need for Context

Implicit in this description is the need for context. It is impossible to provide situation-appropriate information without knowledge of the situation. Requiring the user to explicitly provide this contextual information (by typing, *etc.*) places too much of the interaction burden on the user. Fortunately, computer perception techniques can be used to determine the user's context, trading the burden of explicit interaction for a sensing and modeling problem.[10, 3, 6] This tradeoff is not without cost; computer perception requires more bandwidth and processing power than a traditional user interface, and presents a number of design problems. In particular, the following three questions must be answered for any context-aware application:

1. What type of context (location, activity, *etc.*) is important to the application?

2. How do we sense, classify, and model these

features within bandwidth and computing constraints?

3. How do we best use this information to minimize the cognitive and physical burdens on the user?

Answering these questions requires careful design and empirical testing. Since the appropriate combination of sensors, modeling techniques, and interaction modalities for a particular application cannot be known in advance, context-aware application development requires a flexible platform that provides the widest variety of sensing, computing, and interaction options.

2 Architecture and Application: MIThril and Memory Glasses

In order to focus our research, we chose a single class of application that combines the important features of context awareness and situation-appropriate information delivery: the Memory Glasses. The Memory Glasses is a proactive, context-aware reminder delivery system. The user specifies reminders to be delivered conditioned on context, *e.g.* "The next time I'm near a grocery store, remind me to get milk," or "The next time I talk to my advisor, remind me to ask for a raise." The Memory Glasses represents a broad class of contextual information delivery applications, ranging from medical applications for amnesia and prosopagnosia (face-blindness) to general organization and support for daily living.

2.1 Memory Glasses Platform Requirements

Having chosen the Memory Glasses, we turned our attention to selecting an appropriate platform for its development. The key to making the Memory Glasses work is the ability to sense and classify a useful range of contexts and the ability to deliver information to the user in a way that does not distract from the user's primary task.

Ergonomics and wearability are as important as the flexibility, computing power, and bandwidth of the development platform. Bulky or unsightly equipment that physically or socially encumbers the wearer limits the use and effectiveness of the application and biases user behavior. Based on our analysis, we drew up a list of requirements for the Memory Glasses research platform:

1. Wearability: As much as possible, the hardware should disappear into the user's ordinary clothing, leaving only a minimal user interface. Reliability and ergonomics must be high, weight must be low, and uptime must be long. Ideally, the user puts the system on in the morning, takes it off in the evening, and completely forgets about it in between except when actively using the functionality.

2. Flexibility: The widest possible range of physical and functional configurations should be accommodated by the design so that the widest range of users and behaviors may be studied. Reconfiguring the system should be a simple matter of reconnecting components.

3. Sensing and Bandwidth: A wide range of sensors and protocols should be supported, ranging from cheap off-the-shelf hardware to custom microcontroller-based devices. The on-body sensing bus should provide sufficient bandwidth and flexibility for the simultaneous use of heterogeneous sensors.

4. Interaction: The system should support a range of unobtrusive peripherals, including a lightweight head-mounted display, audio input and output, a chording keyboard for text entry, clothing-integrated peripherals such as embroidered keypads, *etc.* These peripherals should be easily reconfigurable based on application and task, and should form the only visible or noticeable components of the system, "the interface is the computer."

5. Computation and Networking: On-body computing power should be low-power, distributed and scalable, supported by a wired peer-to-peer body network. Since useful resources are likely to be found off the body as well as on it, the system should support low- and high-bandwidth wireless networking options, *e.g.* CDPD cell modem and 802.11.

6. Open Design: All components of the platform, hardware and software, should be fully publishable and unencumbered by restrictive licensing that might discourage collaboration or foster wasted effort through re-invention.

Evaluated against these requirements, existing research platforms are inadequate for developing our research applications. Industrial wearable computers such as the Xybernaut[15] and PC-104 research wearables like the Lizzy[9] provide sufficient computing power and bandwidth, but impose significant social and ergonomic burdens on their users. Current research projects, such as the PLEB[14] and Lart[2] are promising hardware development efforts, but are not focused on the specific problems of wearability and context-aware computing. Light-weight consumer portable devices lack flexibility in configuration and sensing and present limited interaction options. None of the options we investigated were sufficient for our needs, hence our decision to develop a new platform for body-worn context aware computing: MIThril.

3 MIThril Architecture and Implementation

The MIThril architecture grew out of our experience with previous wearable platforms, notably the Lizzy[9] and the Smart Vest[7], as well as industrial wearables like the Xybernaut[15] and consumer electronic devices like the Compaq iPAQ H3600. Each of these platforms has its strengths and weaknesses, but none have proven adequate for our present research agenda. MIThril was developed to combine the best features of existing wearables and meet all of the previously stated requirements for a suitable Memory Glasses application development platform.

3.1 Architectural Overview

The MIThril architecture can be broken down into five major categories: packaging, body bus and sensing, body network and computing, user interface, and software. The clothing-integrated package constrains the overall form, weight, and mechanical properties of the system. The body-bus connects sensors to computing cores, and the body network connects computing cores to each other and to off-body networks (user interface and software are self-explanatory). Diagrams of the logical and physical organization can be found in Figure 2 and Figure 1, and more implementation detail is available through the MIThril project web site[4].

The current "kitchen-sink" MIThril prototype includes one pound (six to eight hours) of lithium-ion batteries, two computing cores (BSEV and CerfBoard with 1GB IBM MicroDrive), an 802.11 bridge, two I^2C-based sensors (Figure 3), seven body-bus cables and two junctions, a body-network hub, a MicroOptical QVGA clip-on HMD and a Twiddler chording keyboard. The total power consumption is at or below four and a half watts when idle and peaks as high as six or eight during periods of high disk-access and 802.11 use. Adding a light cotton/poly shirt "chassis" brings the total system weight to three and three-quarters pounds, lighter than a typical leather jacket. The next version of MIThril, expected to be operational by the

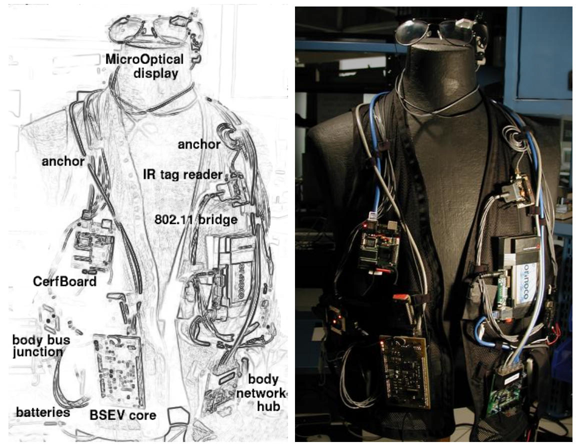

Figure 1: One possible MIThril configuration.

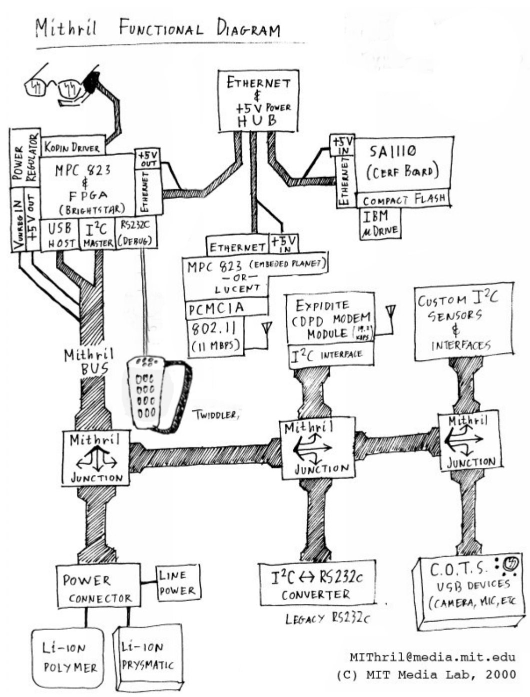

Figure 2: MIThril functional schematic.

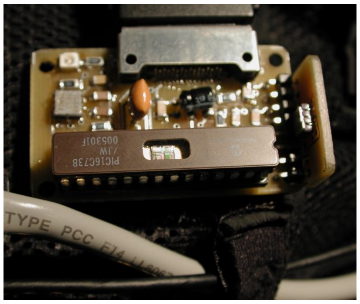

Figure 3: An I^{2}C based three-axis accelerometer for MIThril.

Figure 4: The author and his MIThril.

date of this publication, will incorporate the ETH WearARM core[1] and substantially reduce system weight while improving performance and ergonomics.

3.2 Packaging

Packaging is an extremely important contributor to overall wearability, flexibility, and reconfigurability. The first MIThril package was a light-weight mesh vest suitable for wearing under a shirt or jacket. This package, though not truly clothing-integrated, provided excellent comfort, access, and configurability. We have been developing variants of clothing-integrated vest packaging (from Polar fleece outerwear to dress formal) ever since.

The culmination of our packaging research is a zip-in vest liner not unlike our original mesh vest (see Figure 4). This liner is made of a light-weight, cool mesh fabric and structural belting, and is compatible with a range of outer wear options, from cotton shirts to Armani suits. Off-the rack clothing is easily modified to accommodate the liner with the addition of a single zipper. Distributing the system across the torso maximizes the useful sensor and component real-estate, allowing for the convenient

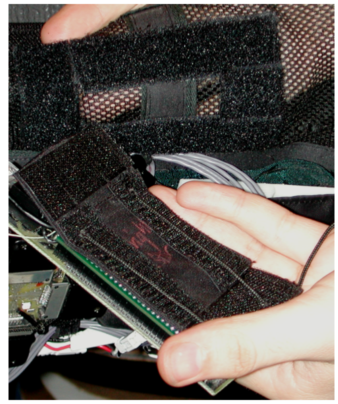

Figure 5: MIThril soft mount.

Figure 6: MIThril cable anchor.

placement of computing cores, microphones, cameras, breathing and heart rate sensors, accelerometers, directional tag readers, *etc.* The package distributes the weight of the system evenly across the shoulders, resulting in a comfortable, balanced feel very similar to ordinary clothing.

All MIThril components are mounted on the liner using the "soft mount" system, a combination of Velcro and tie-on fabric panels (see Figure 5). The soft-mount system allows components to be easily removed and repositioned to accommodate reconfigurations or washing the liner.

Cables are routed on the body using Velcro and neoprene cable anchors (Figure 6). The anchors hold the cables securely but are easy to open for maintenance and fail gracefully under excessive load. Components are placed and cables are routed to avoid the contact-points along the back and shoulders, allowing the wearer to sit comfortably, move naturally, and even fall down without damaging the equipment — as one author inadvertently demonstrated during a cell-phone-induced bike crash (further discussion in Section 5).

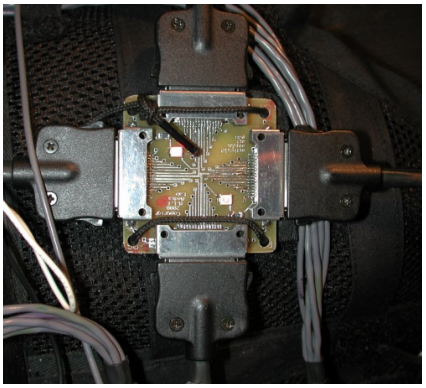

Figure 7: MIThril body bus junction.

MIThril's clothing-integrated design facilitates the development of context-aware applications like the Memory Glasses by creating a comfortable, light-weight package virtually indistinguishable from (and integrated into) the wearer's existing clothing. This package imposes the minimal social and physical burdens on the user, while maximizing the useful on-body real estate.

3.3 Sensors and the MIThril body-bus

On-body connectivity for sensors, peripherals, and power is provided by the MIThril body bus. The body bus, composed of body-bus cables and junctions (Figure 7), is a branching single-connection power/data bus that provides regulated 5V and unregulated 12V power, USB, I^2C, the Dallas Semiconductor one-wire protocol, and three currently unused twisted-pair connections through a stranded 16 conductor cable. The body-bus connectors are locking, strain-relieved, high-torque Hirose 3500 connectors (similar to those used for cell phones) and are rated for 20,000 insertion cycles.

Through its branching structure and multi-protocol design, the MIThril body bus greatly simplifies on-body device placement and cable routing. The connectors and cables are mechanically and electrically stable, robust, and locking. All components are flat and small, making it easy to integrate the MIThril body bus with existing clothing or new designs. The modular design and robust construction makes mechanical failures unlikely and allows for easy reconfiguration and troubleshooting in the field.

The USB protocol provides medium-to-high (12 megabit per second) bandwidth and compatibility with a range of off-the-shelf USB cameras and microphones. However, the USB protocol is complex to implement for custom sensors and peripherals. At the time of this writing, we have functioning USB support for a number of off-the-shelf cameras and audio devices, including the D-Link DSB-C300 camera (OmniVision OV511 chipset) and audio devices by Tenex.

We selected the I^2C protocol to compliment USB on the body-bus. The Philips Inter-IC or I^2C protocol[8] is a multi-device two-wire serial protocol commonly used in industrial and embedded applications. The I^2C protocol provides less bandwidth than USB (400 kbps in High-speed mode) but is easier to implement and suitable for a wide-range of low-bandwidth microcontroller-based sensing applications. We have implemented a number of I^2C-based MIThril sensors, including an IR tag reader (for use with the Crystal tag system[13, 12]), a three-axis accelerometer, a smart battery board for hot-swappable battery power, and an I^2C to RS232C converter for low-bandwidth legacy serial devices.

The Dallas Semiconductor one-wire protocol is used by a variety of single-chip devices, including unique ID tags, temperature sensors, and battery monitor/chargers. At the time of this writing, we have a microcontroller-based implementation of the Dallas Semiconductor protocol and are working on an FPGA-based "native" implementation for the BSEV computing core, described in Section 3.4 below.

The body-bus design facilitates the development of Memory-Glasses applications by providing an integrated framework for combining a range of custom and off-the shelf sensors with an aggregate usable bandwidth of approximately 10 megabits per second. Future high-bandwidth context-sensing applications (on the order of 100 megabits per second) will be supported by running an additional high-speed protocol such as IEEE 1394 or USB2 over the undesignated twisted-pair body-bus conductors.

3.4 Computing cores and the MIThril body network

On-body computing resources are provided by a peer-to-peer network of one or more high-performance low-power computing cores. The only requirement the MIThril body network imposes on the choice of computing core is that all devices must be capable of 10 megabit per second Ethernet and run off of 5V regulated power. (Ergonomics and power-consumption impose additional practical constraints on the choice of computing cores.) In addition, at least one core must support the the MIThril body network and provide the required user interaction resources.

The MIThril body network combines 10 megabit per second Ethernet and 5V regulated power, pro-

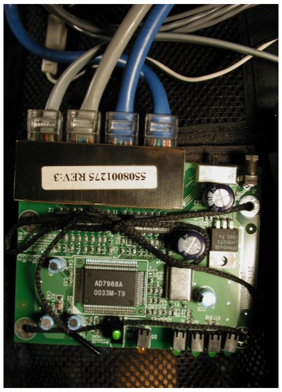

Figure 8: A MIThril body-net hub.

viding a single-connector power/data connection to all body-network devices. A 10-base Ethernet hub modified to distribute power as well as data (See Figure 8) ties the computing cores together, and provides the option of bridging the body network to wired off-body networks through a crossover cable.

The current MIThril prototype employs three cores: the BSEV core, the CerfBoard, and an 802.11 wireless bridge, which are described in more detail below. However, the flexibility of the body network provides a range of choices, from dedicated video or audio processors to specialized network devices. This flexibility allows performance, bandwidth, and power consumption to be tailored to the specific needs of the application, *e.g.* a high-bandwidth Memory Glasses implementation might employ multiple body-bus enabled cores to increase on-body sensing bandwidth, whereas a simple low-bandwidth implementation might employ a single computing core and no other body-network devices.

The BSEV core is a combination of the ipEngine1, an MPC823 based single-board computer from Brightstar Engineering, and a MIThril body-bus/video driver board (See Section 3.5) that provides the body-bus terminus and drives the head mounted display. The ipEngine1 provides a 66 MIPS MPC823 (a PowerPC-derived processor with integrated peripherals), 16 MB of RAM and an Altera FPGA. Combined with the body-bus/video driver board, the result is a moderately powerful and very flexible sensing and user interaction computing core that consumes less than two and a half watts of power. The BSEV core with display and network consumes less than three watts of power.

The SA 1110 Strong-Arm based Intrinsyc CerfBoard is a low-power high-performance computing resource, and in combination with a one gigabyte IBM Microdrive acts as the on-body NFS file server. The CerfBoard provides 200 MIPS of computing power and 32 MB of RAM, allowing it to run complex applications. The total power consumption of the CerfBoard with Microdrive ranges from less than one watt to as high as three depending on disk activity.

The 802.11 bridge is an repackaged Lucent WaveLAN Ethernet converter and Orinoco card, which provides 11 megabit per second wireless networking. Due to the high power consumption of this device (a sustained two watts regardless of network activity) we are investigating the possibility of using a second CerfBoard and a compact-flash based 802.11 interface, such as the Symbol LA4137.

We are collaborating with Urs Anliker, Paul Lukowicz, and Gerhard Troester of the Wearable Computing Lab at ETH in Zurich in the development of the WearARM, a modular high-performance low-power computing core which will provide a superset of the functionality of the Brightstar ipEngine1, the CerfBoard, and the 802.11 bridge. When combined with a body-bus/video-driver board similar to the one currently in use in the BSEV core, it will provided a single-core solution for a wide range of MIThril applications. At the time of this writing, the WearARM core exists as functioning hardware but has yet to be integrated into a functioning MIThril system.

The scalable, heterogeneous computing environment provided by the MIThril body network allows the tailoring of computing resources to meet application needs. For instance, a simple, low-bandwidth implementation of the Memory Glasses might rely on a a single BSEV computing core, whereas a higher bandwidth implementation might rely on dedicated vision or audio processors,

3.5 User Interface Hardware

The choice of user interface is extremely important, since it is only through the interface that the user experiences the functionality of the application. The user interface places the highest demands on the user's attention and represents the user's primary experience of the system as a whole. An important constraint on interface design is the functionality and ergonomics of the interface devices; the MIThril architecture provides both visual and auditory channels for delivering information to the wearer, and audio and key-entry based explicit input.

We chose the the MicroOptical Clip-on QVGA, which is based on the Kopin CyberDisplay 320 Color chip, to be the MIThril head-mounted display. This is a small, light display that clips to the wearer's glasses and provides a full-color quarter-VGA display. The MicroOptical is unobtrusive and obscures little of the user's field of view.

Figure 9: MicroOptical clip-on without IR tag reader.

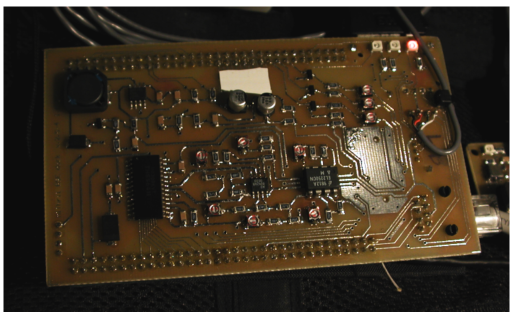

Figure 10: Brightstar ipEngine1 with body bus/video driver board.

The BSEV body bus/video driver board uses the direct output of the MPC823's on-board LCD driver, bypassing VGA signal conversion. This eliminates the need for the bulky VGA driver board and reduces power consumption by almost four watts. In addition, the display driver provides direct control of backlights and signal timing, allowing for software-switching between 60 Hz field-sequential color and 180 Hz high-brightness gray-scale modes.

A range of USB audio devices, such as the microphone/speaker headset made by Tenex, may be used for audio input and output. For key entry, our current MIThril implementation allows for hot-swapping between a modified Twiddler chording keyboard and a modified Palm folding keyboard, and a range of off-the-shelf USB or custom microcontroller-based I^2C devices may also be used.

The flexibility provided by MIThril's interface hardware provides a solid platform for multi-modal interface design.

4 System Software

We chose Linux as the operating system for MIThril because it is open source, has a large and active development community, and is widely deployed in the embedded device market. Linux provides excellent performance and a fully integrated native development environment. Excellent package management is available through the Debian package tools, and literally thousands of software packages are available pre-compiled for both the StrongARM and PowerPC.

We are currently using the Debian Arm distribution for the CerfBoard and WearARM, and a modified Brightstar/Hardhat distribution for the BSEV core, though we are in the process of moving to Debian for that platform as well. The result is a consistent, high-performance operating environment with excellent development tools.

In addition to device drivers for the MicroOptical, I^2C and USB, we have focused on the development of a prototype Memory Glasses application, utilizing the MicroOptical display for output, the IR tag reader for localization and object/person recognition, and the three-axis accelerometer for motion detection and classification. We are in the process of integrating mixed audio-visual feedback and voice recording for spoken reminders.

5 Evaluation and Experience

The success of the MIThril architecture can be measured both in terms of the goals we set for its development and in terms of what we have learned in the process of developing the system.

At the time of this writing, MIThril has been in daily use for over half a year, during which time we have greatly refined its packaging, ergonomics, reliability, sensor/peripheral support, software, and general ease-of-use. We have learned a great deal about engineering reliability and ergonomics in "soft" body-worn computing systems.

One of the first lessons learned was the importance of strain relief and high reliability connectors for on-body connections. Unlike a hard chassis, clothing is constantly flexing and shearing with use. Although the instantaneous torque placed on body-bus connectors is ordinarily low, the cumulative strain from constant motion will cause failures in low-torque-rated low-duty-cycle connectors. Our first MIThril prototype was retired after less than a year of use due to connector failure, prompting a complete reengineering of the body-bus connector system.

Another lesson is the importance of high-quality design and fabrication of the textile components of the system. Although "soft," the textile packaging must be carefully designed and fabricated to meet demanding engineering, comfort, and fashion requirements. For instance, the MIThril vest liner combines multiple fabric types and structural belting to maintain its shape and support the equipment load without sagging or hanging away from the body. Many design iterations went into development of the soft-mount system and the placement and routing of components.

Two particularly interesting and seemingly unconnected hypothesis found support in an unplanned experiment involving the author, a cell phone, a prototype MIThril system with functioning 3-axis accelerometer, and a bicycle. The first hypothesis is that placing relatively small, low-aspect-ratio "hard" parts near to front and sides of the torso would protect them without the addition of a hard shell or extra padding. The second is that sudden interrupts (such as answering a ringing cell phone) are far more disruptive than constant low-level demands on one's attention, such as a small HMD in one's peripheral vision displaying a constant stream of accelerometer data[1].

The results of this experiment included minor bruises and contusions, a slightly damaged bicycle, and a completely unscathed MIThril system that continued to log accelerometer data throughout the duration of the ride and crash. Perhaps this data set will one day be used to train context-aware applications to recognize the important "wearer experiencing cell-phone induced bike crash" context.

In addition to unintentional experiments in terminal ballistics, we are collaborating with the Rochester Center for Future Health to deploy and test a Memory Glasses implementation at the Medical Smart Home[11] to study the benefits and difficulties of building Memory Glasses applications for amnesia and agnosia patients, as well as healthy unimpaired research subjects.

Several simple Memory Glasses demos have been developed, with more sophisticated applications on the way. MIThril is the primary development and target platform for the Enchantment[5] wearable user interface framework.

MIThril is also in full-time use as a general-purpose wearable computer, supporting daily use functions such as recording grocery lists and movie recommendations, conversational note taking, messaging and email, and the writing and typesetting of this paper in LaTeX.

[1] It should be noted that the author has ridden his bicycle many times before and since while wearing a MIThril system without cell-phone interruptions and without ill effect.

6 Conclusions

After almost a year of development, the MIThril architecture has prove itself useful as a platform for the development and testing of Memory Glasses applications and general-purpose wearable computing research. We have learned a great deal about body-worn systems engineering and the development of context-aware applications. The modularity and flexibility of the MIThril architecture has allowed us to continually refine our design and incorporate new features, with many exciting developments (such as the inclusion of the ETH WearARM core) just around the corner. Our work with ETH and the Rochester Center for Future Health demonstrates MIThril's value in fostering collaboration, and we are working to encourage this trend by making the full plans of MIThril freely available on the world wide web.

Having developed MIThril to the point of usability, our real work is only now just beginning. As we turn our attention toward the research applications for which MIThril was developed, its ultimate value will be measured in the degree to which it facilitates the exploration of the last frontier of wearable computing: the domain of everyday life.

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