
THE CHALLENGES OF WEARABLE COMPUTING: PART 2

WEARABLE COMPUTING PURSUES AN INTERFACE IDEAL OF A CONTINUOUSLY WORN, INTELLIGENT ASSISTANT THAT AUGMENTS MEMORY, INTELLECT, CREATIVITY, COMMUNICATION, AND PHYSICAL SENSES AND ABILITIES. MANY CHALLENGES AWAIT WEARABLE DESIGNERS. PART 2 BEGINS WITH THE CHALLENGES OF NETWORK RESOURCES AND PRIVACY CONCERNS. THIS SURVEY DESCRIBES THE POSSIBILITIES OFFERED BY WEARABLE SYSTEMS AND, IN DOING SO, DEMONSTRATES ATTRIBUTES UNIQUE TO THIS CLASS OF COMPUTING.

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Challenges

The most immediately striking challenge in designing wearable computers is creating appropriate interfaces. However, the issues of power use, heat dissipation, networking, and privacy provide a necessary framework in which to discuss interface. Part 1 of this article covers the first two of these issues; Part 2 begins with the networking discussion.

Networking

As with any wireless mobile device, the amount of power and the type of services available can constrain networking. Wearable computers could conserve resources through improved coordination with the user interface. For example, the speed at which a given information packet is transferred can be balanced against latency, energy costs, and financial costs. Often, bits per second per watt is a more meaningful measure of a particular wireless networking technology than maximum

throughput. Another serious issue is open standards to enable interoperability between different services. For example, only one long-range radio should be necessary to provide telephony, text messaging, Global Positioning System (GPS) correction signals, and so on.

For wearable computers, networking involves communication off body to the fixed network, on body among devices, and near body with objects near the user. Each of these three network types requires different design decisions. Designers must also consider possible interference between the networks.

Off-body communications. Wireless communication from mobile devices to fixed infrastructure is the most thoroughly researched of these issues. On the consumer side, analog cellular phones and digital amateur-radio repeaters provided the first glimpse of future problems; these systems would often drop connections as the user moved. Communica-

tions researchers developed systems based on several standards—cellular digital packet data (CDPD), Global System for Mobile Communications (GSM), time-division multiple-access (TDMA), and code-division multiple-access (CDMA)—to help this problem. Today, next-generation communications systems (2.5G and 3G) will further improve connection reliability and aggregate throughput. The “Cellular phones” sidebar discusses networking and interface issues applicable to wearable computers and their design.

No matter what technologies finally dominate, some challenges will remain. First, none of the current networking systems will be ubiquitous. Users will always face situations in which mobile devices will not be in range of a network cell. Although additional cell deployment and satellite use is slowly addressing this problem, it will remain unprofitable to provide coverage for some areas. However, an interesting concept is to employ automobiles as repeaters for the wearable user’s wireless data traffic.¹ Although a wearable computer has a relatively small battery and antenna, cars can carry much larger equipment. In addition, drivers rarely stray further than a few miles from their automobiles. Furthermore, even when driven into a remote location, a car is often within communication range of other cars. For example, imagine a series of cars along rural highways acting as repeaters to route wireless data to a local, fixed networking center, such as a US post office. This wireless service does not need to be real time to provide value; store-and-forward networking has been used successfully with the Internet for decades.

For such a wireless participatory networking scheme to succeed, developers must address standardization, security, quality of service, and synchronization. This style of ad hoc networking of mobile devices complicates traditional issues of resource discovery and routing. Furthermore, mobile nodes traveling at variable speeds create difficulties for many wireless systems. Fortunately, this area of research has become very active in recent years.

Another way to alleviate coverage issues is to employ aggressive caching. By observing the wearer’s network use, the wearable computer can speculate about what the user will access next and cache material using spare network

Cellular phones

Although not wearable computers, the original analog cellular phones provide a study in design constraints related to networking and interfaces of devices. Initially, one of the most important features of these phones was a user interface that resembled, as closely as possible, a push button telephone. This feature provided a key improvement over the half-duplex, push-to-talk walkie-talkies of the time.

As the technology matures, a variety of fundamentally different interfaces are becoming popular, such as instant messaging. Alternative networking paradigms will also appear because of the expense of deploying cellular towers, upgrading infrastructure continuously, and shrinking available bandwidth. These new paradigms will take advantage of asynchronous communication and other modes of human-to-human interaction, such as those used in Internet store-and-forward networks. Even today, cellular phones are becoming more like wearable computers. Higher-end microprocessors, multitasking operating systems, and bitmapped displays now exist in cellular phones. Cellular phone manufacturers embed sensors in these devices to determine if the user is in a meeting or walking on a noisy street. The cellular phone uses this information to determine if the user is interruptible and the mode to use as an incoming-call alert. Indeed, researchers are developing some systems in which the cellular phone communicates a worker’s current task to a remote expert who can provide advice.

bandwidth. When the user is working offline, the system employs this cache and updates any changes when network connectivity becomes available.² But what happens when a conflict occurs? For example, suppose a businessman updates his calendar while disconnected, and, during the same time, his assistant also schedules an appointment. In practice, such conflicts are rare, but this problem raises the issue of where to locate a file’s correct, or master, copy.

Most wireless mobile devices by nature adhere to a thin-client approach to computing. In other words, the device provides just enough processing power, user interface, and data storage to access services that are based on a fixed-infrastructure server located elsewhere. Mobile devices without wireless access, such as the original PalmPilot, provide asynchronous services where docking the device with the fixed network updates the file’s master copy. However, the rapid increase in mobile mass-storage capacity, increasing at a rate that surpasses that of Moore’s law, makes a strong case for the mobile device maintaining the master copy. Today’s ruggedized, pocket-size hard drives can store 48 Gbytes. Soon, mobile users will maintain a terabyte on body, making local storage space a nonissue. In fact, users might prefer keeping all their data with them, making the file data physically secure, accessible at any time, and always the authoritative copy.

Caching, revision control, and intelligent agents can emulate remote access to the user's on-body personal directories when wireless connectivity is unavailable. Although this strategy could prove inconvenient for the occasional third-party user, it gives the wearer the most convenient access. For applications like calendars, the wearer knows her copy is definitive.

Retaining information locally could also help conserve battery power. In terms of power, wireless network access requests are generally more expensive than local access requests. Thus, if the user is responsible for the majority of the data accesses, maintaining a local copy will conserve power. Modeling user activities can also conserve power. Many wireless networks scale transmission power to the minimum necessary to maintain a connection. Thus, transmitting a 10-Mbyte e-mail message when the wearer is near a receiver could require significantly less power than when only a weaker signal is available. If the wearable computer understands a particular message's urgency level and can predict the wearer's future location, it could delay transmission until the wearer is closer to a receiver. In fact, with multiple wireless services to choose from and pricing schemes that depend on time of transmission, the evaluation criteria of when to transmit could extend to include financial cost as well as efficiency. Expected latency could also help determine when and which real-time or interactive services to use.

Interoperability. Unfortunately, the hardware needed to access more than one wireless service burdens the user with extra equipment. Software radios could improve this situation.³ Many wireless-modem components can be emulated using digital signal processing. Downloading the appropriate software to the radio can change its communication standards and protocols (of course, wireless devices will still require certain analog components such as antennas). If this vision proves practical, wearable computers will not only use different wireless networking services based on geographical location, cost, and power, but could also replace certain common, portable consumer electronics, such as GPS receivers, radios, and televisions.

As with mobile ad hoc networking, such wireless services between devices on the body

will also need standards for resource discovery and node arbitration to enable communication. Solving this problem for wearables could prove easier than for ubiquitous computing because a wearer will only occasionally add or remove a device from his body network.

Although on-body communication requires significantly less energy than off-body networks, energy use becomes critical because each device must have its own, relatively small battery. This is a current challenge for the Bluetooth and IEEE 802.15 communities. Some experimental systems, such as BBN's BodyLAN, require as little as 4-nJ/bit to transmit, while maintaining moderate bandwidth.⁴ With such energy conservation, low-bandwidth, on-body sensors and interface devices could last for a year on one charge. As a side benefit, such low transmission power makes US Federal Communications Commission approval significantly easier.

Privacy and contention between different wearers' body networks becomes an issue with on-body wireless networks. Zimmerman's *Personal Area Network* addresses this problem by exploiting near-field effects. In a sense, the wearer's body contains the transmissions, and devices must touch the user to receive a connection.⁵ Post and Orth take a different tack by researching clothing that has embedded electrical components.⁶ By careful use of traditional fabrics and connectors and the design of new conductive threads, these researchers demonstrated functional, washable clothing where the dressing process makes electrical connections. For example, snaps attached with conductive thread can serve as connections among electronics in the shirt, belt, and pants. Such experimentation has also led to new interfaces, including keyboards embroidered onto the user's jacket.

Communicating with near-body objects. Communication with near-body objects provides yet another set of challenges to wearable computer design. Many consumer electronics manufacturers are now proposing networking standards based on mature radio and infrared transceivers. Most of these standards assume that the device has access to a significant energy supply. However, Hull, Neaves, and Bedford-Roberts propose embedding an

RFID tag reader in the user's shirt cuff and passive RFID tags in devices with which the user wishes to communicate or track.⁷ Whenever the user reaches for a tagged device, energy is transmitted wirelessly from the user's shirt cuff to the device, which collects the power and responds with a few bytes of information. This information can be the device's unique ID or, in the future, the current state of the device's low-power sensors. The wearable computer can then use its higher-power wireless connection to transmit these results to the network at large. Thus, a tagged device's location and state is uploaded to the network each time it is moved by a user with a tag reader. This scheme realizes some of the advantages of ubiquitous sensors and networking without the inconvenience and cost of ubiquitous batteries.

The Locust positioning system, shown in Figure 1, provides another example of an implementation of a power-restrictive network scheme. While several technologies provide communication and location information outdoors, the Locust's primary purpose is to provide location information inside a building. Each Locust consists of a microcontroller, infrared transmitter, and infrared receiver. To avoid the maintenance overhead of batteries, each Locust is mounted near an overhead light and generates power with a small solar panel. By mounting these devices close to light sources, the infrared transmitter/receiver pair receives a view of the workspace in a room. The infrared transmitter repeats a unique ID every second with an offset determined by its ID to avoid repeated collisions with other Locust. By listening for these IDs and having a corresponding map of the area, wearable computers can determine their location. The wearable can then repeat this information to networks in the environment, depending on the wearer's privacy preferences. A user can upload small amounts of data to a particular Locust, and the Locust relays this data along with its unique ID. Thus, a user can annotate a given area with specific information for discovery by another, later user. Note that the information can stand alone or act as a pointer to more data, such as sound files, animations, or programs stored on a traditional network and accessed by a user's real-time wireless con-

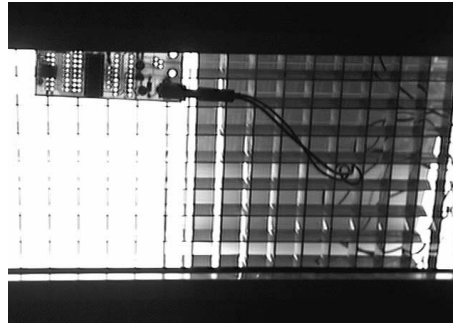


Figure 1. The Locust infrared transponder system mounted in an overhead fluorescent light fixture. The solar cell on the right provides power.

nection. Although researchers have not yet implemented a secure system, a user could target information to one or several users by including a cryptographic key in an upload to a given Locust. In this way, the system creates a simple form of low-power, location-based networking.

Privacy

Those who design systems which handle personal information therefore have a special duty: They must not design systems which unnecessarily require, induce, persuade, or coerce individuals into giving up personal privacy in order to avail themselves of the benefit of the system being designed.⁸

These words, written by Leonard Foner, seem especially applicable to wearable computers, which could become storehouses of users' most intimate information. Indeed, designers of early ubiquitous computing systems often cite privacy as one of the key user concerns in adopting their technology.⁹ User privacy concerns are not equivalent to security concerns. Security involves the protection of information from unauthorized users; privacy is the individual's right to control the collection and use of personal information.⁸ When considering security and privacy, system designers must consider what threats the system might face, such as those posed by crackers, employees, employers, the courts, and so on. For an example of an early wearable computer and how its design addressed

Thorp/Shannon wearable roulette predictor

Probably the first electronic wearable computer mentioned in the literature is also one of the most carefully designed with regard to privacy and unobtrusiveness. Edward Thorp and Claude Shannon designed, built, and field-tested an analog wearable computer that yielded an expected gain of 44 percent in the game of roulette by predicting the most favored octant for the ball to land.

Roulette is a game of chance, popular in many casinos. A small ball spins on a shallow sloped track mounted above a spinning wheel that has numbered pockets to receive the ball. Players bet on the pockets, trying to pick the one in which the ball will land. As the ball and wheel spin, gamblers continue placing bets until it appears that the ball will fall from the track in the next two or three revolutions.

The game was long considered unpredictable and became a challenge to the two Massachusetts Institute of Technology professors who were interested in probability and statistics. Thorp and Shannon determined that by timing the speed of the ball and the wheel and calculating the differential equations that determined their movement, they could determine the ball's path with fair accuracy. By 1961, Thorp and Shannon had created an analog wearable computer to aid a gambler's bets.

Because of the potential serious consequences of being discovered with an electronic device at a gaming table in the early 1960s, unobtrusiveness and privacy were primary concerns. Significantly, not only was it necessary to keep private the information generated by the wearable, but Thorpe and Shannon needed to hide the computer's existence from onlookers. Thus, power, networking, and interface considerations were subservient to minimizing the probability of detection.

The system was divided into separate parts used by an observer and a bettor. The observer wore the computer and timing system, while the bettor wore an earphone so he could receive instructions regarding how to bet. To camouflage the system, the speaker on the bettor's system was placed in one ear canal, and the wires to it were colored to match skin and hair. The observer timed the ball and rotor using microswitches in his shoes. Thus, both the input and output devices were unobtrusive. The computer was placed in a cigarette-package-size box; it remained on the observer. To minimize the risk of detection, an inductive wireless scheme connected the observer's computer to the bettor's receiver. Only surveillance devices that were very close to the system could detect its communications. In designing primarily for privacy, Thorp and Shannon purposely crippled their system; compared to a general-purpose wearable computer, it was a single purpose machine with an awkward interface, limited power system, and rudimentary connectivity. The system was used successfully in a Las Vegas casino in the mid-1960s, but the machine was fragile, preventing large-scale winnings. Worried about getting caught, they delayed revealing their system until 1969, when they described it in a statistics journal.¹

Reference

1. E. Thorp and Anonymous, "Optimal Gambling Systems for Favorable Games," *Rev. of the Int'l. Statistics Inst.*, vol. 37, no. 3, 1969.

the need for privacy, see the "Thorp/Shannon wearable roulette predictor" sidebar.

Depending on the perceived threat, security and privacy concerns can conflict. For example, consider an active-badge system that a company deploys as a security measure. Employees must wear badges at all times to

identify themselves to other employees and security personnel, and to unlock various doors. Each badge continually announces its presence to the environment through radio transmissions. Receivers in the environment report the badge's location to a central system. When combined with other sensors, this system can determine when an individual has entered a restricted space without a badge or appropriate authorization. Although this system could be a highly effective security system, it raises several privacy concerns.

A common user perception about such security systems is that employers could spy on them or monitor activities such as time spent in the restroom or the length of coffee breaks. In fact, employers could install additional, hidden receivers to monitor employee actions covertly. Even if a concerned badge wearer removes the badge for a given situation, the aggregate information collected over several days or months can still reveal behavior patterns.

Assuming that the user does not mind such intrusions or is sufficiently recompensed for them, the security measures a business uses to protect its employee's privacy is still an issue. As an extreme example, consider an employee who has a former spouse stalking her. Does the business sufficiently protect data collected from the security system so that the stalker cannot determine the employee's work hours?

Technically, it is possible to make active badges secure. A badge system can use encryption technology that only gives a master operator access to a given badge's descrambled signature. However, this master operator might be bribed or manipulated into unwittingly revealing critical information.

Legislation could provide another privacy threat to employees. For example, the US Freedom of Information Act and similar state laws might require releasing information that a government employee mistakenly thought was private. In addition, court subpoenas might demand information recovered and stored by ubiquitous computing systems. Already, US authorities have tapped automatic automobile toll-pass systems to help prove court cases. For the active-badge security system, a simple solution is to erase or overwrite records when they are no longer needed. Even so, employees must still trust employers to be diligent in this regard.

Even if technology and policy address these concerns, active-badge systems are vulnerable to yet another form of attack. Simply monitoring the amount of traffic from various badge-receiving stations provides data on a person's path through a building on how many people are in a given area. This traffic analysis can be aggregated or combined with other sources of information to reveal potentially damaging data.

An alternative to active badges is to design systems in which the user solely controls the resultant information. In other words, the user's wearable computer would concentrate, process, and filter any data collected or distributed about the user. In this way, the user controls the degree of functionality and can balance it against the amount of information revealed.

The GPS and Locust (see Part 1) position systems demonstrate this design philosophy. Both systems place transmission beacons in the environment: low earth orbit for GPS and the local environment for Locust. By carrying a compatible receiver operating independently from the infrastructure, users can benefit from these systems without revealing their whereabouts. However, certain functionality, such as letting others inquire about a user's location, would not be available without the user retransmitting his position to the environmental infrastructure.

Although such a retransmission scheme might seem gratuitous, it provides certain benefits. The first is that the user has finer control over what information is revealed. Even if the user does not reveal any information, the wearable computer knows his location—an important piece of contextual information. Another benefit is that the worn component simply listens to beacon signals instead of continuously broadcasting one itself, which gives security badges longer battery life. Also, users might more willingly accept technology in this form. By giving employees explicit control over personal information, an employer shows respect and confidence in employees' use of the technology.

In general, wearable computing could provide users with a sense of control with respect to privacy. This issue will gain in importance as sensing systems become common throughout homes and offices. By limiting a sensor's

physical range and network connectivity to that provided through the user's wearable computer, the wearable computer becomes a natural control point for all user-related information. In some cases, an electric field generated by the wearable computer could wirelessly power the sensors, following the model of passive RFID tags. In this manner, sensors and objects "wake-up" as the user passes through their environment. Without a user with an appropriate power system nearby, the sensors are unavailable. This method helps limit abuse of such systems by a remote third party. When such a scheme is not possible, the user could give explicit permission for the sensing to occur by turning on the sensor's power. The sensor should turn off automatically when it can no longer sense the user or the user's network connection. Although not preventing potential abuses, such schemes help make abuse more inconvenient.

One major challenge to preserving privacy in wearable computing is the dissemination of information and ideas on potential abuses and protection schemes. Wearable computing system designers should have a neutral forum to discuss techniques and introduce standards. Or perhaps the community should devise a privacy protection scheme designed with ratings displayed on various systems and components. For example, a wearable computer component could protect privacy by way of the following barriers:

- *Physical.* In this approach, some mechanism maintains a physical barrier between data and potential abusers. The barriers could range from a system in which users always carry crucial data on their bodies to a methodology that secures data in a safe when not in use. Other physical safeguards could include shielding the wearable computer to minimize unintentional wireless emissions.
- *Technological.* These approaches use security methods such as encryption and biometric identifiers—fingerprints, iris scans, and so on—as barriers.
- *Legislative.* Laws could specify conditions under which privacy is considered violated. The law could tailor associated penalties to particular technologies,

ensuring relevance and avoiding misinterpretation in court.

- *Social.* Wearable systems could use existing social conventions to build barriers. For example, systems could store sensitive data in physical articles—such as data repositories resembling diaries or wallets—that a particular culture would normally consider personal.
- *Obscuring.* The wearable computer could hide sensitive information in directories with large quantities of nonsensitive information. Thus, a casual investigator could not look at all the files to determine which are the most revealing.

Although some of these protections are very weak, different combinations allow a user to specify various levels of inconvenience for a would-be interloper. In some cases, the user might want the barriers to be breached given enough persistence. For example, if the user has a serious accident, the user might want colleagues to discover his medical history, whereas in normal circumstances he would consider this information private. Perhaps a medical information memory card stored in the user's wallet would provide an appropriate level of protection against casual prying. Such a card would let bystanders help the user in an emergency. However, if the main concern is exploitation by the user's medical insurance company, more levels of security would be necessary. With care, wearable designers can specify barrier combinations to adapt to the changing political, technical, and social climates in different markets and geographic areas.

Interface design

In the following discussion, the term *interface* is used as a generalization to refer to the numerous fields that address human and computer interaction. This includes, but isn't limited to, human-computer interfaces, psychophysics, human factors, ergonomics, industrial design, and fashion. Wearable computing interfaces are a topic for an entire textbook; this article cannot begin to summarize the work in the field to date or even the areas yet to be explored (for an overview, see the *Proceedings of the IEEE International Symposium on Wearable Computers*).¹⁰ Instead, this discussion is meant to stimulate curiosity in the field.

Clothing, design, and fashion. Wearable computing represents an unusual intersection of science, engineering, design, and fashion. The same basic computer components found in a mainframe also comprise a wearable, but design decisions for wearables must account for the restrictions of portability and usability over the need for speed and throughput.

In addition, there is a surprising social aspect to wearable computing. The design, tailoring, and expense of a wearable computer can reflect the user's taste and importance, as does a banker's choice of business suits. Natick Army Research Lab researchers have indicated to the author that in the armed forces, wearers' perception of design and expense affects their acceptance and opinion of the most basic supplies, such as mountaineering boots.

To make a computer wearable for an extended period of time, designers must carefully determine size, body placement,¹¹ clothing type,⁶ and wired interconnections to other components. This situation could reverse the normal design process for computers; with wearables, developers might first decide on a form factor and then determine functionality and associated electronics. Such a philosophy resulted in the PalmPilot when other stylus-based handheld devices were failing.¹² Unlike much of computer science and electrical engineering, where ungainly prototypes might not affect an experiment's quality, simple variations in the form factor of a research-grade wearable computer could prove significant.

Peripheral interfaces: Making simple things simple and complex things possible. To improve portability, peripherals for wearable computers tend to be small. For example, the Twiddler one-handed keyboard can fit in a pocket, and the flat panel display in a pair of MicroOptical eyeglasses is about the size of a grain of rice. Unfortunately, unlike computer processors, there is a limit to how small these devices can become. The resolution of the human eye limits a usable display's size and resolution. Similarly, the size of the user's fingers limits the placement and number of keys on a keyboard. Wearable peripheral designers must consider trade-offs between usability, portability, and unobtrusiveness for every device they make.

As previously discussed, one vision of wearable computers involves a body-centered wire-

less network through which the user can integrate peripherals simply by pocketing them. Such a system eliminates redundancy in portable consumer electronics; it could also enable interfaces that would otherwise prove too costly to implement because of the repeated design cost for each independent device. More importantly, such a system structure encourages the design of specialized peripherals for particular tasks. The "A day in the life" sidebar presents a scenario that illustrates this point.

Some wearable computer users might prefer general-purpose equipment that allows maximum flexibility and constant availability. Unfortunately, such general-purpose systems provide a bit of a conundrum socially. Onlookers do not know if the wearer is using the system as a camcorder, a cellular phone, a text editor, or a game system. Thus, an onlooker does not know if she can conveniently interrupt the user. Of even greater concern to the onlooker is whether or not the wearer records their conversation covertly. While virtually undetectable video and audio recording equipment has been available for some time, as evidenced by investigative news programs, the similarity of head-up displays to camcorder eyepieces causes confusion with onlookers. In the past, the form factor of portable devices helped constrain their perceived uses. For example, a microphone hanging from a box at a reporter's side designates the box as an audio recording device. However, with wearable computers, the form factor and uses are not yet commonly known. Providing some external cue about the tasks being performed by the wearer from minute to minute could prove important as wearable computers become more widespread.

Intellectual tools

One of the early applications of computers was to calculate ballistic trajectories, a task for which the human mind is not well suited. In artificial intelligence, research efforts try to create machines that perform tasks the human mind and body do perform well. An interesting challenge that serves as a compromise is to create systems that augment a user's natural abilities through computational components. This idea is not new; the history of computing is filled with systems and philosophies described

A day in the life

A fictitious police detective's typical day demonstrates how wearable computers may benefit from specialization of peripherals: When documenting a crime scene, the detective removes a small camera and microphone from his car's glove compartment and fastens them to his lapel. The camera stores video on the detective's pocket wearable. With a small keyboard attached to his belt, the detective privately adds text annotations to the video stream. At the office, the detective stashes the camera and keyboard in his coat pocket, and approaches a large screen and interface area festooned with a variety of knobs normally associated with video editing. The wearable interfaces with this equipment, and the detective spends the next few hours splicing together segments of his field observations to make his report. Given an insight by his editing, the detective decides to question a suspect. He holsters his gun, which can only be activated to fire when it is kept within two meters of his wearable. The detective borrows a pair of sunglasses with a small display, camera, and microphone embedded in them. He also picks out a longer-range network transceiver so that the others at the station can monitor his progress. As he questions the suspect, the detective compares the suspect's answers to his report and images from the crime scene displayed on the sunglasses. As a result, he discovers an inconsistency in the suspect's story and decides to arrest him. Although not as convenient as the lapel camera to manipulate, the sunglasses' camera performs well, inconspicuously documenting and reporting the suspect's resistance to arrest. Back at the police station, another police officer, who monitors all detectives' progress via their long-range transmitters in the field, alerts nearby units to the situation. Back-up officers respond to the location, and the suspect is arrested safely.

The peripherals in this scenario were designed for specific tasks and form factors. Using each device was simple—any software or hardware reconfiguration on the wearable was performed transparently when the user approached the peripheral. All the peripherals linked into the detective's personal machine, allowing maintenance of crucial information on the detective's body. The detective makes an active choice in what functionality he wishes to carry versus the inconvenience of added weight and bulk the peripherals might cause.

by scientists who approached this problem in some form, for example, Bush's *Memex*, Wiener's *Cybernetics*, Licklider's *Man-Machine Symbiosis*, and Englebart's implementation of NLS/AUGMENT, to name a few.

In the pursuit of such an interface, wearable computing provides a set of advantages not available before. Wearable computers are physically close to the user, highly portable, quickly accessed, and designed to consume a fraction of the user's full attention. PDAs, the commercial devices most similar to a wearable, provide a contrast to these traits. Users often store PDAs in a pocket or carrying case. So, although PDAs are physically close, it can take users a significant amount of time to access the interface. In addition, the use of a stylus-based PDA requires both hands, and the interface requires most of the user's visual attention. Thus, it is difficult to use PDAs while, for example, walking down the street, repairing an automobile, or even having a

conversation. However, a wearable equipped with a display built into eyeglasses and a one-handed or speech-driven interface lets the user concentrate on a primary task while the wearable provides information support. For example, in repairing a car, a mechanic only has to make a small eye movement to refer to the car's technical manual in a head-up display.

User attention is the scarcest resource for wearable computing. In particular, hand-eye coordination is at a premium as the user lives in the physical world while accessing virtual information. Interfaces should provide the most support for the smallest investment of attention diverted from the user's primary task. This idea is at odds with the window-, icon-, menu-, and pointer-driven interfaces generally found on desktops; desktop applications often assume that the application itself is the primary focus of the user's attention. Hence, wearable computer systems might not use traditional GUIs for many tasks.

Note taking and immediacy of interface. A wearable equipped with a head-up display and one-handed keyboard allows rapid note taking in most situation. In some cases, the wearable provides a less obtrusive and more efficient method of recording information than is possible with traditional means, such as pen and paper. For example, in the author's case, typing on a one-handed keyboard takes half as much time as writing by hand.

Wearable computer users who use their machines during conversation tend to optimize their systems such that they can begin taking notes within two seconds of realizing the need. Given this level of speed and access, everyday users generally take a huge variety of notes, ranging from how to fix a given piece of equipment to what they need to do in the next 10 minutes. Researchers have noted informally that in some domains, access to the interface in under two seconds results in significantly more use than systems that require a longer delay.¹³ This "two second rule" provides an initial heuristic for defining the acceptable delay in accessing the interface for wearable systems.

Perception and context. A wearable can also retrieve the context in which notes were taken; such context is useful for indexing. Given a

user and a set of goals, context is defined as those environmental features not created explicitly for input to the system.¹⁴ Lamming showed how context could be effectively used with Xerox's PARCTabs.¹⁵ His Forget-me-not system sensed particular office activities, such as personal location, encounters with others, workstation activities, telephone calls, file exchanges, and printing. It demonstrated the use of complex queries to augment memory. For example, suppose the user remembers that he discussed a business plan with a colleague a week ago and was interrupted by a telephone call. However, he does not remember who called or why it was important enough to interrupt the conversation. Forget-me-not lets the user search these events from the past and, from the context of the interruption, provide the user with the name of the person who called and a record of the user's actions afterward, which might illuminate the importance of the call.

More sophisticated on-body perception systems can capture a more complete sense of context. Through sensors placed near where the user's natural senses are located, the wearable receives a first-person view of the wearer's interactions with others and the world. Recently, computer vision researchers have begun experimenting with wearable computers. Clarkson uses unsupervised learning on wearable-based audio and low-resolution video to identify interesting events during the user's everyday life.¹⁶ These characterizations can act as additional features when looking for particular pieces of information. Although not wearable, Moore has demonstrated a vision system that identifies objects, such as a book or keyboard, by tracking how the user manipulates these objects.¹⁷ Schiele and Starnier have developed wearable gesture and object recognizers.¹⁸ Although these are research systems, they demonstrate how a wearable computer's first-person perspective could capture the day-to-day experiences of wearers without burdening them with having to specify explicitly what to capture.

Just-in-time information. Capturing information does not have much meaning unless it is indexed and retrievable in a timely fashion. A major question in the wearable computing community is how to present information to

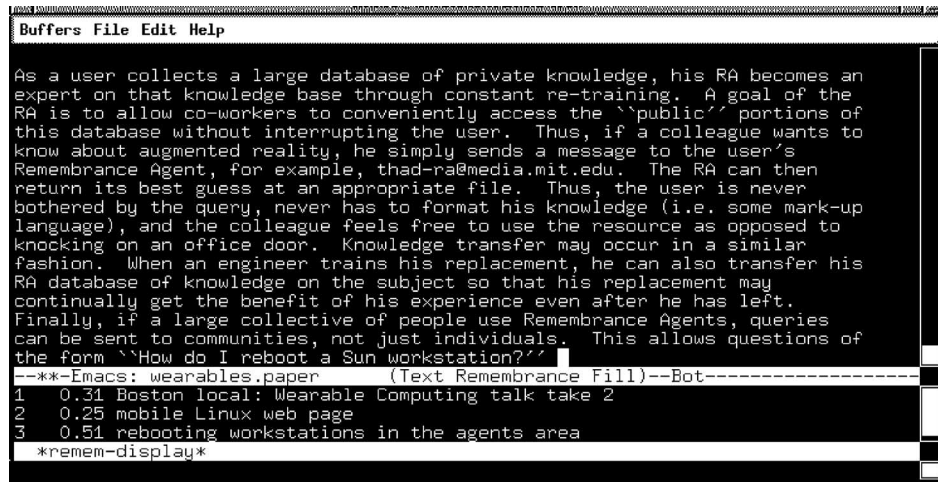


Figure 2. Remembrance Agent. Every 10 seconds, the current text in the top buffer forms an automatic query that returns the one-line summaries of potentially interesting documents in the bottom buffer.

a wearer. Researchers at Carnegie Mellon University have reported several successes using wearable computers for inspection, maintenance, and repair, especially in industrial and military domains.¹⁹ However, in her doctoral thesis at the Georgia Institute of Technology, Ockerman reports that her wearable task guidance system inhibits experienced pilots' performance in inspecting their aircraft.²⁰ The apparent discrepancy is more than likely due to the users' relative experience levels with the task and the authority they assign to the wearable computer. When given a checklist, Ockerman's experienced users tend to over rely on it. To help prevent this problem, the wearable interface should encourage the user to exercise judgment and physically touch the equipment. Adapting the user interface based on active sensing of the inspected object might alleviate this problem. Providing overviews of the task's purpose and each step's context in the checklist has been shown to improve performance. In short, with experienced users, wearable computers should provide formal structure yet encourage independent thought and adaptation of the interface to the situation.

While Ockerman's task guidance systems expect explicit user interaction, such as when the wearer notes an observation or signals that a subtask is complete, another style of interface suggests pieces of information based on current context. Rhodes describes these as just-in-time information retrieval agents or

"software that proactively retrieves and presents information based on a person's local context in an accessible yet nonintrusive manner."¹⁴ Creating these mobile, nonintrusive computer interfaces is a distinct challenge and research focus.

A particular just-in-time information retrieval agent of interest is the Remembrance Agent.¹⁴ Although information retrieval systems exist for many applications, almost all of these systems concentrate on written text and query-based information retrieval on demand. For example, they can answer questions such as "When is that conference's paper deadline?" or "Who's an expert on this particular algorithm?" However, they do not help the user remember to ask a question or what question to ask. The Remembrance Agent addresses these problems. Its associative forms of recall might remind a user that an important conference exists, or that there are references to a particular algorithm the user might have missed.

The Remembrance Agent, shown in Figure 2, performs this task by continuously displaying relevant information to an individual user in his current context. In its current form, the Remembrance Agent software uses text that a user is reading or writing as a query into its relevance engine. At the bottom of the user's screen, one-line summaries of potentially useful documents (e-mails, papers, books, notes, and so on) appear as a list in order of potential relevance. If a document is

indeed interesting, this summary alone may be a sufficient reminder for the user of the document's existence. Alternatively, if the summary intrigues the user, he can view a full annotation with a simple sequence of key-strokes.

..... Augmented reality overlays

information on the physical

world.

.....

Although early wearable prototypes of the Remembrance Agent attempted to couple audio and visual perception to information retrieval, the resulting systems were not practical for everyday use.¹⁸ However, recent advances in desktop-based systems that recognize gesture, faces, and speech indicate that these types of mobile systems could become feasible in the near future.

Facilitating collaboration

Many occupations are inherently mobile, with spontaneous meetings often happening away from any desktop. In such cases, wearable computers might aid communication and collaboration. Kraut et al. found that remote assistance significantly improves task performance in wearable applications.²¹ In this study, a technician wore a head-mounted camera and display combination to enable a remote expert to see the technician's workplace and to display appropriate manual pages. Kortuem identified several collaborative primitive functions that wearable computers can exhibit, including remote awareness, presence, presentation, pointing, and manipulation. Kortuem experimented with body-stabilized spatial information displays to support 3D collaboration. Although the state of the current hardware often interferes with exploring these principles, an intuitive collaborative interface that does not overwhelm the wearer's attention seems feasible.²²

An intriguing collaboration idea exploits communities of wearable agents acting on behalf of their owners.²³ These agents negotiate for cooperation during physical encoun-

ters between wearers with selfish, and possibly conflicting, goals. For example, if two package delivery drivers encounter each other at a drop-off point, their wearables can compare delivery schedules and determine if, by exchanging packages, the drivers can minimize their routes. Fickas et al. simulated such negotiations in large-scale wearable communities and explored the role of deception as well as methods for building such communities.²³

Tailoring augmented-reality systems

Many systems presented in this discussion involve information interfaces that are portable and personal, and demand as little user attention as necessary. In some forms of augmented reality, however, the information has immediate bearing on a physical object and its properties. In such cases, coupling the virtual interface to the hand-eye coordination and visual attention needed to interact with the physical object is appropriate and even desirable. Examples of this are augmented realities that provide sensory enhancement or that help compensate for physical handicaps.

As stated earlier, augmented reality overlays information on the physical world. For example, a doctor could wear a head-up display to see the results of an X-ray overlaid on an actual patient. In such situations, the information provided by the head-up display, in this case, the skeleton, is not incongruous with the patient's body presented to the doctor's unaided eyes. In fact, the head-up display needs to accurately track the patient with low latency to maintain the doctor's illusion of seeing through the patient. This visualization's accuracy and stability is especially important when performing surgery. During surgery, updating the visualization in a timely manner is also important. Thus, coupling the visualization to the surgeon's actions is beneficial.

On the other end of the spectrum, some augmented realities might need only the loosest coupling. For example, augmented realities might trigger audio events based on which room the wearer visits or even go so far as to communicate to the wearer primarily through ambient interfaces. Between these two extremes lies a continuum of interfaces for further research.

As mentioned earlier, one particularly intriguing idea in augmented reality is to extend the Web to physical reality. Figure 3

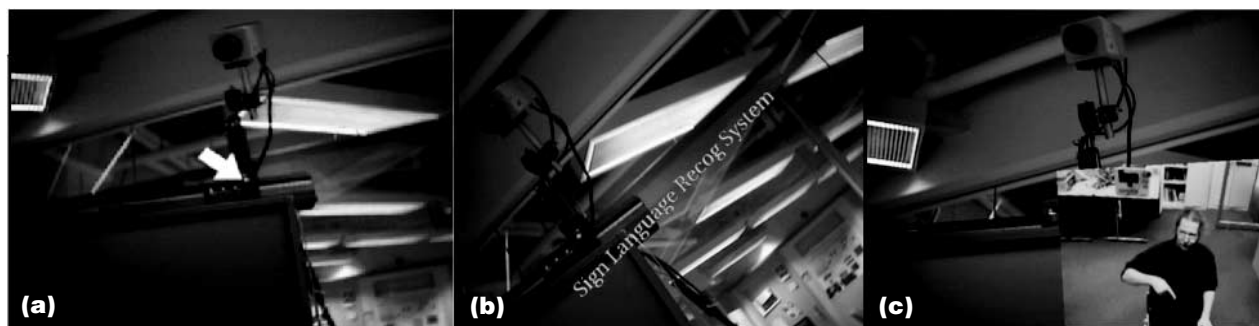


Figure 3. Augmenting reality with hypertext links. When a computer vision system first locates a tag, it renders an arrow on top of the live video in the wearer's head-up display; the arrow indicates a hyperlink (a). If the user shows interest by staring at the object, the system displays appropriate text labels (b). If the user approaches the object, the system shows movie sequences or 3D graphics (c).

demonstrates an early implementation of such a system using computer vision and head-up displays.¹⁸ The user wears a combination head-up display and camera. Computer vision algorithms continuously search the video images for unique tags that indicate an object has information associated with it. Computer graphics then overlay the user's visual field to communicate this information. In the system shown in Figure 3, when the system first locates a tag, an arrow is rendered to indicate a hyperlink. If the user shows interest, the system displays the appropriate text labels. Figure 3b shows the overlying text rotating in conjunction with the tag, demonstrating that the system can recover rotation with respect to the user's head. If the user approaches the object, the system displays 3D graphics or movie sequences, as shown in Figure 3c.

In the past decade, several researchers have begun addressing how to improve the sensing and human-computer interface problems of augmented-reality systems. The problems associated with a "real World Wide Web" are an area of active research, but a true field test cannot occur until the requisite equipment becomes more accessible and a sufficiently large population of users is supportable.

In many senses, this augmented-reality extension of the Web combines many properties of the intellectual tools described earlier. A wearer can attach annotations to physical objects, thus performing a form of context-dependent note taking. Letting others access these notes achieves a form of asynchronous collaboration. Indeed, coupling notes to a physical context or to a set of actions that trig-

ger them creates a form of just-in-time information retrieval agents. Augmented reality could also assist synchronous collaboration between Web users by enabling shared visualization of file systems, design tools, and information searches.

Hardware and software engineering

In creating wearable systems, many trade-offs occur with respect to the challenges discussed in this article. Balancing these characteristics during design, runtime, and maintenance is the domain of software and hardware engineering. Academic and industrial groups are beginning to organize collaborations and workshops to explore what software and hardware engineering mean in the wearable computing domain, but much work remains.

Most general-purpose wearable computers described in the literature do not address the complicated design choices implicit in such systems. Devices like those discussed in the pacemakers (see Part 1) and cellular phones sidebars of this article, use special-purpose wearable computers and related infrastructure hardware. Each design prioritizes one attribute significantly more than others. Although progress in hardware will enable more functionality in a wearable computer, the balance between privacy, power, networking, and interface will be continually revisited with each new development in the field.

Wearable computing pursues an interface ideal in which the computer persists and provides constant access to information

Further resources

- <http://www.cc.gatech.edu/ccg>
- <http://www.media.mit.edu/wearables>
- <http://www.charmed.com>
- For a complete bibliography for this article, visit <http://computer.org/micro>.

services, senses and models context, augments and mediates the user's interactions with the environment, and interacts seamlessly with the user. Much work remains. Perception on the body is a relatively new endeavor since appropriate sensors are just now becoming available. While much study has centered on low-attention interfaces for automobiles and aircraft, little has been done for users of personal head-up displays. Most ambitiously, wearable computing will enable and encourage development of intelligent agents that model the user's minute-by-minute behavior in an effort to predict future needs and goals. In the words of Licklider, if even partly successful, "the resulting partnership will think as no human brain has ever thought."

MICRO

Acknowledgments

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This article is dedicated to the memory of Claude Shannon, hacker par excellence.

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