The Challenges of Wearable Computing: Part 1

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 as they balance innovative interfaces, power requirements, 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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•••••• Wearable computing can describe a broad range of devices and concepts. At the time of this writing, *wearables* are generally equated with head-up, wearable displays; one-handed keyboards; and custom computers worn in satchels or belt packs. Figures 1 through 4 show members of the Massachusetts Institute of Technology's Wearable Computing Project with some of their wearable devices. Unfortunately, the public often characterizes the field by its gadgetry instead of its goals. Ideally, wearable computing can be described as the pursuit of a style of interface as opposed to a manifestation in hardware. This article develops goals and challenges for wearable computing, and promotes discussion in design techniques by suggesting methods, albeit sometimes fanciful, of addressing these challenges.

What is wearable computing?

Several authors have defined wearable computers by desirable characteristics. For example, Rhodes states that wearables provide portability during operation; enable hands-free or hands-limited use; can attract the user's attention, even when not in active use; can run continuously; and attempt to sense the user's current context.[1] Kortuem et al. employ similar criteria but use the term *augmented reality* to describe "the user interface technique that allows focusing the user's attention and presenting information in an unobtrusive, context-dependent manner."[2] Meanwhile, Mann describes wearables as constant and always ready, unrestrictive, not monopolizing of user attention, observable and controllable by the user, attentive to the environment, useful as a communication tool, and personal.[3]

This article defines wearable computing through the effort to achieve a hypothetical, ideal wearable computer. Much of this philosophy reflects the concept of a *cyborg* or a *man-computer symbiosis* as introduced in 1960. Manfred Clynes and Nathan Kline originally coined the term cyborg to describe a human and machine combination where the interface becomes a natural extension of the

Figure 1. Wearable computing platforms worn by members of the Massachusetts Institute of Technology's Wearable Computing Project. *Photo by Sam Ogden*


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Buffers File Edit HTML Help
intensive site due to scanned
pages.  If you are having very
delays in reading these pages,
the "no images" option on your
browser. </P>

<IMG WIDTH=600 HEIGHT=6
SRC="blue-divider.gif"
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<h2>What's a Wearable?</h2>

To date, personal computers have not
lived up to their name.  Most
machines sit on the desk and interact
with their owners for only a small
fraction of the day.  Smaller and
--**-Emacs: index.html      7:43pm 0.25
Write file: ~/*scratch*
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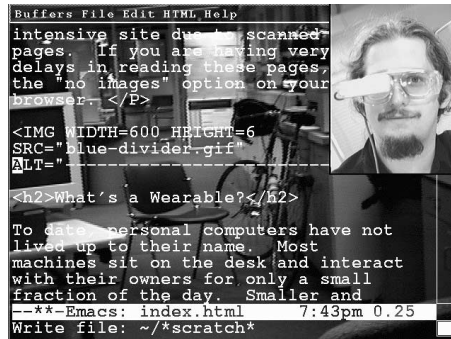
Figure 2: Private Eye head-up display and simulated view. The wearer's visual system "shares" images from both eyes to create the illusion that the wearer sees through the opaque display.
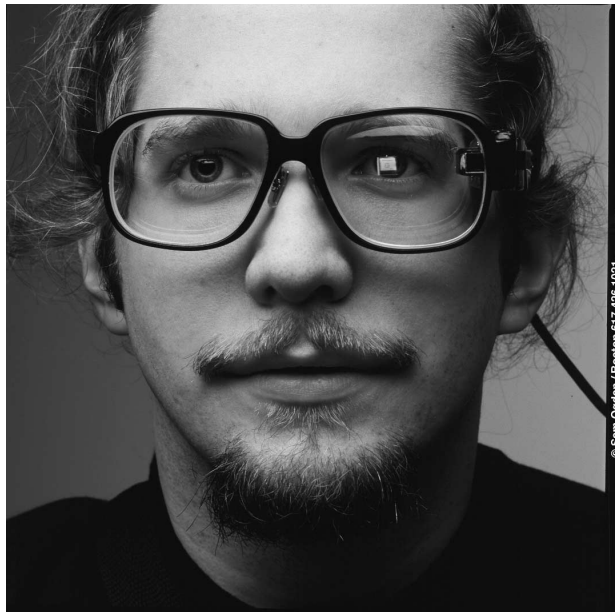

Figure 3: MicroOptical's display embedded in a pair of eyeglasses. The actual display is in the earpiece. An optical path deflects the image through the lens to a half-silvered mirror that reflects the image to the user's eye. *Photo by Sam Ogden*
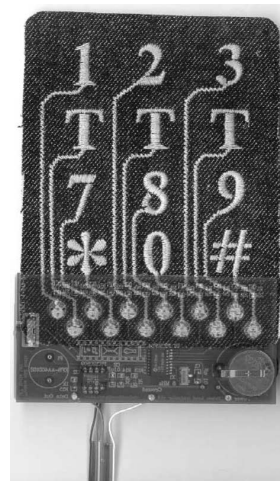

Figure 4: Functional chording keyboard embroidered into a jacket. *Photo courtesy of Rehmi Post and Maggie Orth*

user. This interface would not require much conscious attention, such as when a person rides a bicycle. Although Clynes and Kline's aim was adapting humans for the rigors of space travel, the same concept might be applied to systems that assist the user on other physical and intellectual levels. J.C.R. Licklider expresses this in *Man-Computer Symbiosis* where he defines the title term as

…a subclass of man-machine systems. There are many man-machine systems. At present however, there are no man-computer symbioses…. The hope is that, in not too many years, human brains and computing machines will be coupled together very tightly and that the resulting partnership will think as no human brain has ever thought and process data in a way

not approached by the information-handling machines we know today.

Ideal attributes

To achieve the tight partnership suggested by Licklider, the computer must be a user's constant companion. It must share the experiences of the user's life, drawing input from the user's environment to learn how the user reasons and communicates in relation to the world. As it learns, the computer can provide increasingly useful and graceful assistance. Ideally, a wearable should have several key attributes.

Persist and provide constant access to information services. Designed for everyday and continuous use, the wearable can interact with the user at any given time, interrupting when necessary and appropriate. Correspondingly, the user can access the wearable quickly and with little effort. Such a device must be mobile and physically unobtrusive.

Sense and model context. To provide the best cognitive support for the user, the wearable must observe and model the user's environment, the user's physical and mental state, and its own internal state. In some cases, the user could provide explicit contextual cues to help the wearable in its task. To provide parity, the wearable should inform the user of its own status, either through an explicit display or through subtle background cues. In addition, the wearable should make its models observable so that the user can identify misunderstandings and explicitly tutor the wearable when necessary.

Adapt interaction modalities based on the user's context. The wearable should adapt its input and output modalities automatically to those that are most appropriate and socially graceful at the time. For example, while attending a meeting, the wearable could communicate with its user through a head-up display. However, when the user enters his or her car to drive home, the wearable could switch to an audio-only interface. In many instances, the computer interface will be secondary to the user's primary task and should demand the minimal necessary amount of the user's attention. In addition, the interface should guarantee privacy of interaction when appropriate,

adapt to its user over time, and encourage personalization of its interface.

Augment and mediate interactions with the user's environment. The wearable should provide universal information support in both the physical and virtual realms. For example, the wearable should automatically gather information and resources relevant to a particular physical location and filter this information based on the user's current needs and preferences. The wearable should mediate between automation or computation in the environment and the user to present an interface consistent with the user's preferences and abilities. In addition, the wearable should manage potential interruptions, such as phone calls or e-mail, to best serve its user.

Obviously, these attributes are ambitious, requiring a very detailed user model of the wearer. However, in striving to achieve this goal, research efforts could reveal new insights about intelligence and human-computer interfaces.

Why use wearable computers?

Some people wear too many computers. A businessman in Hong Kong might carry a personal digital assistant (PDA), a cellular telephone, a pager, a laptop computer, an electronic translator, and a calculator wristwatch. These devices all contain very similar components: a microprocessor, memory, a screen, a keyboard or input stylus, a battery, and, in some cases, a wireless modem.

As technology evolves, portable consumer devices are beginning to have similar components as well. For example, computer-driven MP3 players replace CD players, solid-state audio digitizers replace portable Dictaphones, digital cameras are beginning to supplant film-based cameras, and digital camcorders have outmoded their analog counterparts. The main distinctions between these devices are the interface and the application software. Wearable computers could exploit the commonality in components to eliminate cost, weight, and redundancy and to improve connectivity and services.

For example, imagine a box the size of a deck of cards that encloses a powerful yet energy-conserving CPU and a large-capacity data storage device. This pocket-sized wearable

computer has one output display—an LED to indicate that it is on and that its wireless network is functioning. This wireless network connects peripherals to the wearable computer in a radius of about two to three meters centered at the body.

By choosing peripherals, the user defines this wearable computer's functionality. For example, wireless earphones allow access to MP3 files stored on the wearable computer's hard drive. Adding a walnut-sized camera and the appropriate software transforms the wearable into a camcorder. With an Internet modem, the wearable becomes a pager, cellular phone, Web browser, and e-mail reader. Connecting medical sensors to the wearable concentrates many diagnostic and recording devices into one unit.

Thus, wearable computing and a wireless body-centered network reduce component redundancy. In addition, functionality increases as derivative services arise, leveraging the convergence of media on the body. The portable-consumer-electronics market will become fertile ground for rapid innovation. Companies can quickly respond to a new need or niche market with an appropriate peripheral or software without redesigning subsystems for each iteration. Sophisticated portable electronics will become cheaper and more powerful for the consumer, and the computer industry will have a new, attractive upgrade path to pursue.

Mediate interactions

The introduction of the windows, icon, menu, and pointer desktop metaphor in GUIs provided a means for user interfaces to mediate between applications and the user. Similarly, wearable computers will help provide a consistent interface to computationally augmented objects in the physical world. For example, the Gesture Pendant, shown in Figure 5, acts as a universal remote control that replaces button pushing with simple gesture recognition. The Gesture Pendant is worn as a broach or necklace and detects hand movements performed in front of the body. The device recognizes these gestures to provide control over electronics. Since many functions are similar across devices, one gesture could provide an intuitive command for many devices. For exam-
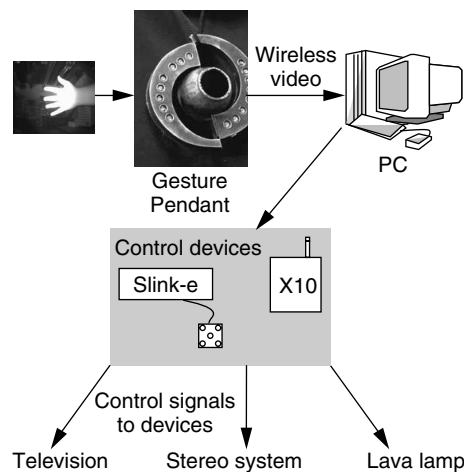

Figure 5. Using a near-infrared computer vision and lighting system, the Gesture Pendant lets users control appliances through gestures. The Slink-e converts control instructions from a computer's serial port and the X10 is a home automation control standard that communicates with signals over electrical lines.

ple, depending on which object the wearer faces, raising or lowering a finger in front of the pendant might raise or lower the volume of a stereo, increase or decrease the temperature setting on a thermostat, and brighten or dim light settings on a lamp. Thus, the user could define or learn one interface and then apply it repeatedly to many different devices, depending on context.

Imagine a more general-purpose wearable computer that, through software, adapts to provide a consistent interface to any electronics or computer systems in the environment. For example, in a hotel, the wearable might provide access to the room's alarm clock and television through an interface consistent with the user's home system. The infrastructure needed for such interface adaptability will be a boon to the handicapped. An individual can carry an interface appropriate for his abilities that automatically adapts to the services provided by the electronics in the environment. For example, for a blind user of an automated teller machine, the wearable can provide an audio version of the interface.

Aid communication

The wearable can also assist in human-to-human communication. Imagine that an English-speaking traveler from the US visits Mexico. He could use a general-purpose wearable to scan menus and signs and translate them into English. Similarly, when conversing, the wearer can use a head-up display, as shown in Figure 3 and a one-handed keyboard to quickly search an online phrase book for appropriate English phrases, which the user or even the wearable then says in Spanish. Going further, the wearable could employ speech recognition and directly translate English into Spanish. Such systems are no longer purely speculative. Carnegie Mellon researchers have already demonstrated an English-to-Croatian wearable speech translator for use in the Bosnian peacekeeping mission.[4]

Wearable computers can also help manage interruptions in the user's daily life. With the spread of cellular phones, more people are aware of the inconvenience of an untimely interruption. Through sensors such as accelerometers, microphones, and caller identification devices, wearable computers can determine the user's current context and adapt appropriately. For example, if the user is in a noisy environment, an audible ring might be appropriate. However, interrupting the user during a business meeting is inappropriate, unless the identity of the caller is the user's spouse and the situation is an emergency. In such instances, the wearable might switch to an instant messaging service displayed in the wearer's eyeglasses so that the wearer can assess the situation and excuse herself gracefully, if needed.

Provide context-sensitive reminders

Context-sensitive interfaces will become very powerful with wearable computers. Instead of simply acting as a virtual secretary, the wearable could be proactive and intimate, listening to the wearer's conversations and providing reminders as appropriate. Such reminders might be the text of the last e-mail message exchanged between the conversation's participants, the definition of an unknown word, or recommendations on local restaurants that both participants would enjoy.

Augment reality

Augmented reality overlays information-rich virtual realities onto the physical world. Wearable computers make mobile augmented reality practical. In a sense, augmented reality is a combination of the application domains described previously: mediating between the user and environment, assisting human-to-human communication, and providing context sensitive reminders.

Instead of restricting the Web to desktop computer monitors, wearable computers will let any object or location in the physical world serve as a hypertext link.[5] Museum visitors and tourists will discover information about artifacts simply by staring at them, triggering associated hypertext presentations. By allowing annotation, augmented-reality objects will let friends and colleagues leave private messages for each other at offices, restaurants, or street corners.

The creation of an augmented reality infrastructure will lead to unexpected derivative uses. A powerful scenario involves advertising, sales, and distribution.

> As a wearer walks down a New York City avenue, a billboard advertising jeans begins transmitting information to the user's wearable computer. Because the user is occupied looking at his calendar, the wearable computer conveys to the billboard that all but the most interesting advertising overlays are turned off, and the billboard begins a negotiation process for the user's attention. After asking the wearable the user's trousers size, a piece of information the user has given his prior approval to make public, the billboard hooks into the supplier's local inventory and discovers that they have an overstock in that size. The billboard offers its product at a discount. The new price causes the wearable computer to whisper the offer discretely in the user's ear. The user, now interested, turns to see an animated advertisement tailored to his interests overlaid on the billboard. Deciding that the product is worth the price, the user commits to the purchase and the wearable computer transfers money and exchanges address information with the billboard. The billboard reroutes an express delivery truck to drop off the jeans at the wearer's house within the next two hours.[6]

Obviously, this form of just-in-time information delivery can provide powerful tools for the retail, advertising, and delivery industries. In general, wearable computers could lead to unanticipated hardware, software, and service industries, possibly triggering changes similar in scope to those of making the Internet publicly available. However, many technical, social, and logistical challenges lie ahead in creating appropriate devices for consumer markets.

Challenges

To provide wearable computing, designers must overcome significant challenges. As with any computing system, good software and hardware engineering methodologies enable stable advancement. Indeed, wearable computing has inherited many of the systems issues with which the general computing community grapples. However, wearables represent a current extreme in computing because researchers have not thoroughly studied the area's design trade-offs. To encourage discussion, this article presents possible approaches to these challenges, ranging from the immediately practical to the fanciful. However, each idea is fashioned from practical issues and applications in the field.

Each of these issues is closely related to the others, and a design change to correct deficits in one often affects the others. The most immediately striking challenge is in creating appropriate interfaces for wearable computers. However, the issues of power use, heat dissipation, networking, and privacy provide a necessary framework in which to discuss the interface.

Power use

Power is perhaps the most limiting factor in mobile technology. Although transistor density continues to shrink exponentially, battery energy density, whether measured by volume or by mass, increases linearly with a relatively shallow slope. A mobile device's mass is often determined more by its power source than the underlying electronics. Given the continuing financial costs and design constraints of advanced energy technologies, a small-device designer is well advised to determine the maximum allowable cost, size, and weight for the battery before designing the electronics, functionality, and packaging. In

designs where peripherals are connected wirelessly to a central mobile device, supplying power becomes even more complicated. Each peripheral requires its own power source, which may fail independently of the other components, possibly resulting in unreliability or high maintenance costs.

Wearable computing presents particular variations of this problem. Ultimately, wearable computers are clothes. A user might wear a display in a pair of sunglasses, keep a computer in a belt buckle, and have a keyboard woven into a jacket.[7] When the wearable computer's functionality is spread among subsystems distributed over the body, power distribution becomes complicated. If the components' battery lives are too short, the user will soon get frustrated with the effort needed to keep the system powered. One solution is to create long-lasting power supplies. For example, plutonium-238 power sources, such as those implanted with pacemakers in the late 1980s, can last for decades (see the "Pacemakers and Power" sidebar). However, such exotic materials are currently impractical because of political issues. Another possibility is to use primary chemical batteries, which are relatively long lasting compared to rechargeable ones. However, large-scale adoption would result in serious environmental disposal issues.

The obvious alternative is secondary batteries. However, rechargeable batteries require that the user remember to maintain them, which can be a problem. For example, digital phones with multiple days of battery life still run out of power—often because users forget to charge them. For wearable computers that are part of a wearer's everyday life, recharging the batteries should be tied to everyday actions. The user needs to create a daily routine that includes computer maintenance, similar to cleaning contact lenses or eyeglasses. For example, designers could make a computer with 16 hours of battery life that would recharge in the eight hours that the user sleeps. Other natural breaks that could provide recharging time are at meals and at the beginning and end of the workday.

Ideally, recharging the wearable computer and its peripherals should be implicitly coupled with the normal acts of dressing. For example, an inductive charger hidden in the

Pacemakers and power

Pacemakers demonstrate a design extreme that general-purpose wearable computers do not generally address. The pacemaker example helps illustrate the complicated design choices designers make in terms of power use in a wearable computer. Through electrical currents, pacemakers regulate the beating of the wearer's heart. Advanced pacemakers have computer-controlled components that monitor the wearer's heart rhythm, breathing rate and depth, body motion, or muscle activity to determine whether the heart rate needs adjusting (rate-responsive pacing). Some pacemakers even have external components that let a patient or caregiver monitor the pacemaker's status. These advanced pacemakers satisfy many definitions of wearable computers.

Since pacemakers are implanted, there is a high penalty for replacing batteries or for connecting to the pacemaker's circuitry for reprogramming. Exotic power sources such as lithium-iodide batteries and plutonium-238 cells minimize the need for reimplantation. In addition, medical personnel upgrade pacemaker software via electromagnetic couplers placed outside the body. The pacemaker can also provide diagnostic information through these couplers.

Pacemakers could, in theory, be fitted with powerful transmitters and encryption systems to communicate their information securely through today's cellular phone infrastructure for easy access by medical staff to patient data and programming updates. However, the overwhelming emphasis on power limits such gadgetry.

This trade-off is common in the more general field of neuroprosthetics. Designers in this field develop computer controls for artificial cochleas, artificial retinas, and deep brain stimulators for the treatment of epilepsy and Parkinson's disease. They remain alert for the effects of new features on their devices' power consumption and flexibility in adapting to future updates.

surface of the wearer's bedroom dresser could wirelessly charge electronics placed there—similar to setting down cuff links or eyeglasses. Such systems seem feasible given the existence of similar home electronics such as inductive stoves and inductively charged electric toothbrushes. Similarly, the act of placing shoes in a closet or a jacket on a hanger could establish wired or wireless connections embedded in these items for recharging a computer.

Alternatively, some wearable peripherals could generate power from human actions or from the phenomena they sense. For example, the energy expended in pressing buttons on a one-handed keyboard might power the keyboard. One of the most intriguing possibilities currently being researched are shoes that generate power from the wearer's heel strike or bending of the sole while walking.[8]

An esoteric but theoretically possible method of powering on-body electronics is to use the same power source as the wearer—that is, food. This idea could have military applications where providing separate supply lines for the soldier and his or her electronics is inconvenient. If the soldier's on-body electronics used foodstuffs for its operation, the soldier could decide whether to eat the food or use it to power communications to his home base. Although certainly a fanciful idea now, work in robotics could make this feasible.

Yet another alternative is to scavenge power from the environment. For example, it is possible to recover an average of 50 W/m^2 from rigid outdoor solar power panels aimed at the sun (assuming a 20 percent efficiency conversion of a 250 W/m^2 solar load). However, flexible solar cells appropriate for use on clothing have significantly less conversion efficiency and would not always have direct sun exposure. Available power would also drop significantly when a wearer stepped indoors. In general, the main constraints of scavenging light to power wearable electronics are needing a large surface area on the device devoted to recovering energy and aiming the device toward a light source.

Another possibility is to recover power from radio transmissions, as, for example, in the crystal radio sets that hobbyists use to receive AM radio broadcasts. In fact, in most populated areas, similar devices can recover milliwatt-level power. Of course, just as with solar power, the size and direction of the receiving antenna could make such a device inconvenient to wear.

However, imagine an on-body wireless networking system in which radio transmissions from an on-body base unit provide power.[9] Although only low-power microcontrollers and sensors could use such a system, the concept of a combination wireless network and centralized power supply is attractive. Passive radio frequency identification (RFID) tags exploit a similar idea. A tag reader generates an electric field that the tag harvests for power whenever it is brought within range. When the tag has stored enough power, it generates a unique digital radio signature that announces its presence to the reader.

Heat dissipation

The companion problem to power use is heat dissipation. When specifying processors for wearables, MIPS per watt is a much more important parameter than raw processing speed. Power density of (the now older) 0.6-micron microprocessor chips surpassed that of a kitchen

hot plate's heating coil; the problem is only becoming more severe.[10] Current desktop processors can require over 100 W of power. Putting such a processor in a pocket-size device would create the equivalent of wearing several high-power soldering irons. Given that devices in contact with human skin should not much exceed 40° Celsius, using such processors would be extremely difficult in a small design.

In fact, heat dissipation is one of the foremost limiting factors in the design of high-end laptops, and providing heat dissipation is a source of considerable expense. Designs must channel heat away from the processor, or else it will suffer thermal shutdown. Of course, manufacturers have made progress in making processors tolerate higher temperatures, but according to a 1998 study, processors exceeding the 40-W range cost an additional US dollar per watt per chip.[11] Current laptops use expensive heat spreaders and evaporative heat pipes to transfer heat to other surfaces of the laptop for radiative and convective cooling. Of course, another solution is to make lower-power processors and components.

Several additional alternatives could be feasible for wearable computers. With a wearable computer, the user's thermal environment changes routinely, often to the computer's benefit. For example, even a weak airflow can significantly increase heat dissipation. While walking, the airflow about an arm-mounted computer is significantly enhanced by the arm's pendulum-like movement. In fact, the airflow along the forearm is turbulent in many situations, effectively doubling the heat dissipation of calmer air movement.[6] Also, if the wearable computer is filled with nonconducting fluid such as 3M's FluorInert, movement will create currents that help transfer heat away from the processor to the computer's packaging.

Another idea is to use the wearable computer's close proximity to the human body to aid in cooling. For example, a forearm-mounted wearable computer could dissipate heat directly to the user—a greatly appreciated situation in winter.[6] This idea is not so unusual; a similar computer cooling effect already occurs when users place modern notebook computers on their laps. In addition to exploiting changes in ambient and skin temperatures, the wearable might take advantage of the cooling effects of the user's perspiration, for example, when he or she enters an air-conditioned building. Temperature feedback mechanisms, already common in microprocessor design, could be adapted for these tasks.

More aggressive systems might employ thermal regulation via active thermal reservoirs. For example, cooling systems could exploit the heat capacity of the computer's batteries. While charging, users could chill batteries so that the wearable computer could transfer heat into them during operation. For some batteries, this warmth could increase battery life. In addition, by employing active cooling elements such as Peltier junctions, the computer might cool the batteries or components during times of low ambient temperature. Thus, the computer would have access to a thermal reservoir during times of heat stress. Unfortunately, current Peltier device inefficiencies make this method impractical in the near future. However, a water reservoir, perhaps stored in a sponge, could provide a heat reservoir through evaporative cooling.

Phase-change materials provide an attractive method to compensate for lack of cooling.[12] Such materials can absorb a tremendous amount of heat while they maintain the same temperature as they transition from solid-to-liquid or liquid-to-gaseous phases. Thus, if the wearable computer's casing encapsulates such a material, the produced heat can be directed into changing the phase of the material while the unit is turned on. When the unit is off, it would cool, causing the encapsulated material to revert to its original phase. An ideal material would require a large amount of heat to change phases. It would also have its first phase change at approximately body temperature and its second phase change at approximately 41° Celsius. In this manner, temperature plateaus occur at both a standard user comfort level and the maximum allowable operating surface temperatures. Although such a material probably does not exist, at least in a nontoxic form, combinations or stratified layers of materials could prove adequate.

Finally, careful use of resources might help avoid many heat generation crises for a wearable computer. For example, developers could write applications for wearable computers with heat dissipation in mind. The computer can delay disk maintenance, downloads, and batch jobs until it senses a cooler environment.

Further resources

Depending on perceived user need, a slower network connection might be appropriate to allow more time for heat dissipation. With such methods, performance is reserved for user interactions, and the effective average power consumption can be higher without causing uncomfortable spikes in heat generation.

MICRO

Acknowledgments

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