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Wearable Computing: A First Step Toward Personal Imaging

Miniaturization of components has enabled systems that are wearable and nearly invisible, so that individuals can move about and interact freely, supported by their personal information domain.

Can you imagine hauling around a large, light-tight wooden trunk containing a co-worker or an assistant whom you take out only for occasional, brief interaction. For each session, you would have to open the box, wake up (boot) the assistant, and afterward seal him back in the box. Human dynamics aside, wouldn't that person seem like more of a burden than a help? In some ways, today's multimedia portables are just as burdensome.

Let's imagine a new approach to computing in which the apparatus is always ready for use because it is worn like clothing. The computer screen, which also serves as a viewfinder, is visible at all times and performs multimodal computing (text and images).

With the screen moved off the lap and up to the eyes, you can simultaneously talk to someone and take notes without breaking eye contact. Miniaturized into an otherwise normal pair of eyeglasses, such an apparatus is unobtrusive and useful in business meetings and social situations.

Clothing is with us nearly all the time and thus seems like the natural way to carry our computing devices. Once personal imaging is incorporated into our wardrobe and used consistently, our computer system will share our first-person perspective and will begin to take on the role of an independent processor, much like a second brain—or a portable assistant that is no longer carted about in a box. As it "sees" the world from our perspective, the system will learn from us, even when we are not consciously using it.

Such computer assistance is not as far in the future as it might seem. Researchers were experimenting in related areas well before the late seventies, when I first became interested in wearable computing devices. Much of our progress is due to the computer industry's huge strides in miniaturization. My current wearable prototype,[1] equipped with head-mounted display, cameras, and wireless communications, enables computer-assisted forms of interaction in ordinary situations—for example, while walking, shopping, or meeting people—and it is hardly noticeable.

DEVELOPING COMPUTERS TO WEAR

In 1968 Ivan Sutherland described a head-mounted display with half-silvered mirrors that let the wearer see a virtual world superimposed on reality.[2,3] His work, as well as subsequent work by others,[4] entailed a serious limitation: Because the wearer was tethered to a workstation, generally powered from an ac outlet, the apparatus was confined to a lab or some other fixed location.

My experiments in attaching a computer, radio

(a)

(b)

Figure 1. (a) The unique capabilities of a wearable personal computer-imaging system and lighting kit let me create expressive images that transcend the boundaries of photography, painting, and computer graphics. (b) The system consisted of a battery-powered computer with wireless communications capability, so that I was free to roam untethered.

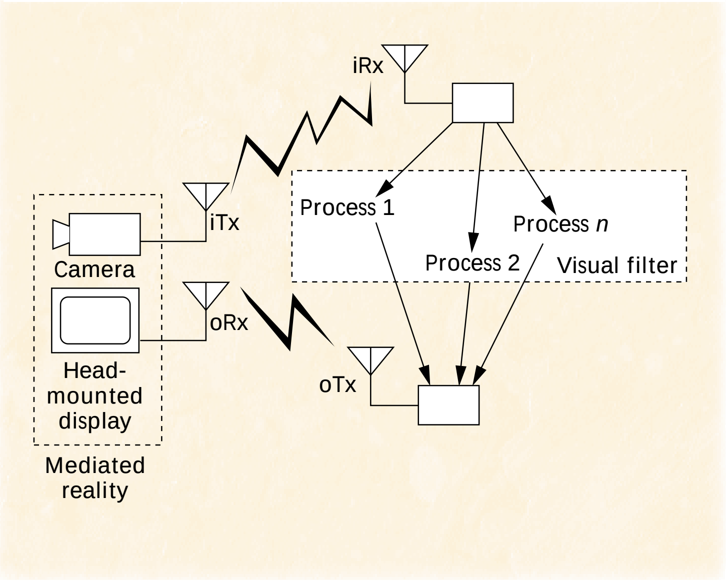


Figure 2. An experimental apparatus for wearable, tetherless, computer-mediated reality. The camera sends video to a remote supercomputing facility over a high-quality microwave communications link. The computing facility sends back the processed image over a UHF communications link. "Visual filter" refers to the process(es) that mediates the visual reality and that may insert virtual objects into the visual stream.

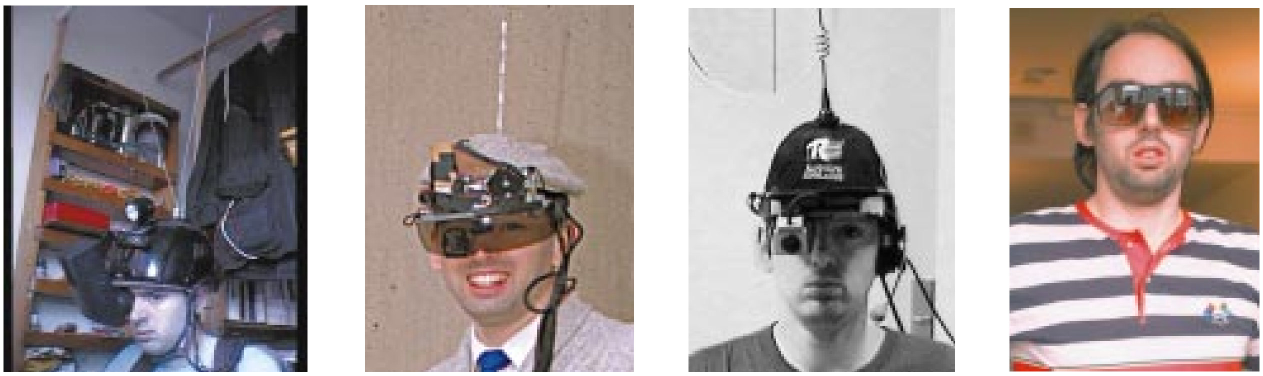
equipment, and other devices to myself culminated in a tetherless system that lets me roam about the city. I can receive e-mail and enjoy various other capabilities exceeding those available on a desktop multimedia computer. For example, family members watching remotely can see exactly what I see and, while I am at the bank, remind me by e-mail to get extra cash. Or I can initiate communication, using RTTY (radioteletype), to ask what else I should pick up on the way home.

This new approach to computing arose from my interest in the visual arts—particularly still-life and landscape imaging in which multiple exposures of a static scene could be combined and illuminated by a variety of light sources. Figure 1a shows an image made using this original "light-painting" application.

To explore such new concepts in imaging and lighting, I designed and built the wearable personal imaging system shown in Figure 1b. At the time (around 1980, while I was still in high school), battery-operated tetherless computing was a new modality, as the laptop computer had not yet been invented. My invention differed from present-day laptops and personal digital assistants in that I could keep an eye on the screen while walking around and doing other things. A CRT on the helmet presented both text and images, and a light similar to a miner's lamp helped me find my way around in the dark. I carried an electronic flash lamp that let me capture images in total darkness. An array of push-button switches on the flash-lamp head controlled the computer, camera, and so forth.

The incredible shrinking computer

Even 10 years later, during my experiments in the early 1990s, the computational power required to perform general-purpose manipulation of color video streams came in packages too unwieldy to be worn in comfortable clothing. I was forced to use special-



(a) (b) (c) (d)

Figure 3. Progressive miniaturization by the computer industry has enabled wearable devices to become less obtrusive over the past 16 years. (a) 1980 prototype with a 1.5-inch CRT; (b) late 1980s multimedia computer with a 0.6-inch CRT; (c) a more recent commercially available display; (d) a current, nearly undetectable, prototype consisting of eyeglasses, a handheld control, and a computer worn in back under the shirt.

purpose hardware with good video processing capability remotely by establishing a full-duplex video communications channel between the clothing and the host computer or computers. I used a high-quality communications link to send video from the cameras to the remote computer(s) and a lower quality communications link to carry the processed signal from the computer back to the head-mounted display. Figure 2 diagrams this apparatus, which let me explore applications that will become possible when miniaturization puts today's supercomputer power into tomorrow's clothing.

When I brought my apparatus to MIT in 1991, I installed two antennas on the roof of the tallest building in the city. Later I found that if I moved one of the antennas to another rooftop, the inbound/outbound channel separation improved dramatically. The apparatus provided good coverage on the university campus, moderate coverage over a good part of the city, and some coverage in a nearby city.

Advances in miniaturization helped to streamline the equipment over the years. In Figure 3a I am wearing a 1980 prototype of the experimental system. The 1.5-inch CRT was unwieldy and required a well-fitted helmet to support its weight. (For viewing the CRT, I have used, in various embodiments of the head gear, a lens and mirror at a 45-degree angle, a partly silvered mirror, and reflections off eyeglasses.) Two antennas, operating in different frequency bands, allowed simultaneous transmission and reception of data, voice, or video. Alternative versions of the communications apparatus included a slightly less cumbersome clothing-based antenna array (hanging behind me at the upper right in Figure 3a) comprising wires sewn directly into the clothing. Substituting this clothing-based array let me clear doorways and ceilings during indoor use.

With the advent of consumer camcorders, miniature CRTs became available, making possible the late 1980s eyeglass-mounted multimedia computer shown in Figure 3b. Here I am using a 0.6-inch CRT facing down (angled back to stay close to the forehead). This apparatus was later transferred to optics salvaged from an early 1990s television set. Though still somewhat cumbersome, the unit could be worn comfortably for several hours at a time. An Internet connection through the small hat-based whip antenna used TCP/IP with AX25 (the standard packet protocol for ham radio operators).

The prototype in Figure 3c incorporates a modern commercial display product made by Kopin, an American manufacturer of head-mounted displays, along with commercially available cellular communications. With the advent of cellular and other commercial communications options, a radio license is no longer needed to experience "online living." Unlike my earlier prototypes, this system was assembled from off-the-shelf components. Though it is much improved, I expect to do even better: The prototype shown in Figure 3d—still under development—is nearly undetectable.

APPLICATIONS

Just as computers have come to serve as organizational and personal information repositories, computer clothing, when worn regularly, could become a "visual memory prosthetic" and perception enhancer.

Edgertonian eyes

Early on, I experimented with a variety of visual filters[5] as I walked around. Each of these filters provided a different visual reality. One filter applied a repeating freeze-frame effect to the WearCam (with the cameras' own shutters set to 1/10,000 second). This video sam-

Figure 4. Six frames of low-resolution video from a processed image sequence. My computer recognizes the cashier and superimposes a previously entered shopping list on her image. When I turn my head to the right, the list moves to the left on my screen, following the flow-field of the video imagery coming from my camera. Note that the tracking (initially triggered by automatic face recognition) continues even when the cashier's face is completely outside my visual field, because the tracking is sustained by other objects in the room. Thus, the list of items I have purchased from this cashier appears to be attached to her. This functionality can provide a clear recollection of facts during a refund transaction.

ple-and-hold technique let me see the unseeable: writing on moving automobile tires and the blades on a spinning airplane propeller. Depending on the sampling rate of my apparatus, the blades would appear to rotate slowly backward or forward, much as objects do under Harold Edgerton's stroboscopic lights.[6]

Beyond just enabling me to see things I would otherwise have missed, the effect would sometimes cause me to remember certain things better. There is something very visceral about having an image frozen in space in front of your eyes. I found, for example, that I would often remember faces better, because a frozen image tended to remain in my memory much longer than a moving one. Perhaps intelligent eyeglasses of the future will anticipate what is important to us and select the sampling rate accordingly to reveal salient details.

Finding our way around

We've all been lost at one time or another. Perhaps, at the end of a long day in a new city or a large shopping complex, you can't find your car or subway stop. One way I guard against such lapses is by transmitting a sequence of images to my WWW page. Then if (when) I get lost, I browse my WWW page to find my way back. An advantage of having the image stream on the Web is that friends and relatives with wearable Web browsers can see where I have been and catch up with me. This constitutes a type of shared visual memory.

Footwear offers yet another opportunity for help in orientation. Mark Weiser of Xerox PARC, commenting on IBM computer scientist Tom Zimmerman's computerized shoes, predicts that someday customers walking into a store will pick up floor-plan data from their shoes that will guide them to the merchandise they're shopping for.[7]

Zimmerman was not the first to propose shoe-based computing. In the late 1970s, a group of researchers known as the Eudaemons were building shoe-based computers for use in physical modeling of chaotic phenomena[8]—or more specifically, for bettering their odds at roulette. One person would enter data (clicking with the toes) while watching the ball; another person would receive the data and try to predict the octant the ball would land in.

Figure 5. Using a visual filter such as this in the personal visual assistant may help a person with very poor vision to read. The central portion of the visual field is hyperfoveated for a high degree of magnification while allowing good peripheral vision.

Homographic modeling

Recently I reported on a wearable apparatus[9] that can help us identify faces by comparing an incoming image to a collection of stored faces. Once the wearer confirms a match, the "video orbits" algorithm[10] that I developed enables the system to insert a virtual image[11] into the wearer's field of view, creating the illusion that a person is wearing a name tag. As Figure 4 shows, the name tag will stabilize on the person even though the image field moves. The homography of the plane is estimated and tracked throughout, so that even when the objects being recognized fall outside the camera's field of view, tracking continues by the homography alone.

Personal visual assistant for the visually challenged

With its spatial filtering capability, a head-mounted apparatus can assist partially sighted individuals.[12] Worn over the eyes, it computationally augments, diminishes, or alters visual perception in day-to-day situations in real time.[5] For example, Figure 5 shows how a visual filter might assist in reading. The portable system, made from a battery-powered color stereo display having 480 lines of resolution, is shown in Figure 6. The wearer's only visual stimulus comes from the computer screens, since in this case the glasses are totally opaque. I call this experience *fully mediated reality*.[5]

Figure 6. My early 1990s apparatus for wearable, tetherless, computer-mediated reality included a color stereo head-mounted display with two cameras. The intercamera distance and field of view approximately matched my interocular distance and field of view with the apparatus removed. Communications equipment was worn around the waist. Antennas, transmitter, and so forth, were at the back of the head-mount to balance the weight of the cameras in front.

SOCIAL ASPECTS

The early prototypes were quite obtrusive and often made people ill at ease, but more recently the apparatus has been gaining social acceptance. I attribute this partly to miniaturization, which has allowed me to build much smaller units, and partly to dramatic changes in people's attitudes toward personal electronics. With the advent of cellular phones, pagers, and so forth, such devices may even be considered fashionable.

When equipped with truly portable computing, including a wireless Internet connection and an input device like those pictured in Figure 7, I find that people I talk with aren't even distracted by my looking at the screen. In fact, they cannot discern whether I am looking at my screen or at them, because the two are aligned on exactly the same axis. The problem of focal length can generally be managed by setting it so that the screen and anyone I'm talking with are in the same depth plane.

With enough light present, images can be incorporated into the note-taking process in a natural manner, without distracting the other person. Even in low light—for example, while talking with someone outdoors after dark—a small flash, shown in Figure 7a, can be used during a conversation without breaking eye contact. The only distraction is the light from the flash itself, which may startle people at first. (An infrared flash would be less obtrusive.)

Some years after I developed the keyboard/control system in Figure 7a, a commercial product—the mouse shown in Figure 7b—appeared. Its numerous buttons could be used to type or to control various other functions. In the future, of course, we will not need keyboards and mice at all. A goal of personal

(a) (b) (c)

Figure 7. Hand-held keyboards, mice, and controls. (a) My early prototype (incorporating one microswitch for each finger and three possible microswitches for the thumb) was built into the handle of an electronic flash lamp and allowed simultaneous one-handed control of computer, camera, and flash lamp. (b) Modern off-the-shelf mouse/keyboard combination made by Handykey Corp. The mouse consists of a tilt sensor inside the housing. (c) Virtual mouse. Camera in eyeglasses tracks finger, which controls a cursor, allowing the user to look at a luxo lamp through the glasses and draw its outline on the computer screen.

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