Promoting Wearable Computing:
A Survey and Future Agenda

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Abstract

This paper is composed of a survey on wearable computers and a research agenda to further pursue topics in the communication area. We begin with a brief walk-through of the terminology and examples, followed by motivation originated from two historical trends – enhancing human biological ability and increasing resource accessibility. Then, we investigate the existing technologies and relevant research proposals in four major areas: I/O interface, searching, communication, and power. After addressing some concerns on wearable computer's practicality, we proposed a number of small-scale projects aiming at developing high-level communication protocols suitable for the wearable computing environment.

1   Introduction

Wearable computers in a loose sense are computers people can wear *effortlessly*. In a stricter sense[12], wearable computers should run *continuously*[1] and be operated *hands-free*. This stricter definition helps distinguish wearable computers from portable ones. For instance, pocket watches are not wearable computers in a sense that people need at least one hand to hold them and sometimes another hand to open the covers. Wristwatches, in contrast, can be easily flipped over and read when both hands are engaging other activities.

Many small laptops (Figure 1, left[6]), are not wearable computers either. They do not last long enough to meet the continuous run requirement[2]. Wearable computers like MIT's Lizzy[22] (Figure 1, right) can run much longer because of carefully selected power-conservative components and efficient batteries.

The wearables and small laptops differ in I/O features as well. To operate hands-free, wearables are usually equipped with head-mount or eyeglass-based displays (Figure 2, left) and one-hand keyboards (Figure 2, right) or microphone with speech processing software. Figure 3 shows a IBM prototype of ThinkPad 560X shrunk to 10.5 oz (approximately. 300 gram) and to a size small enough to fit into regular pockets. This prototype, introduced in September 1998, consists of a 233 MHz Pentium CPU, 64 MB DRAM, 340 MB IBM micro hard disk, a micro head-mount display, and a microphone with speech processing software.

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[1]Ideally, the power units should run as long as possible, at least from 9 A.M. to 5 P.M. with no or very short interruptions.

[2]One can carry extra batteries to make the portable computers run continuously but extra batteries also mean extra burden which violates the 'effortless use' criteria.

Figure 1: Left: Two Popular Mini-notebooks, Toshiba Libretto 50 (Top) and Sony PCG-C1 (Bottom). Right: A User Wearing MIT's Lizzy Design.

Figure 2: Typical I/O Devices: left picture is a micro-display to be clipped onto a eyeglass frame; right picture shows a twiddler keyboard with integrated mouse functionality.

Relationship With Ubiquitous Computing   Ubiquitous computers, in the purest form of definition[18], are computers invisibly embedded in the environment and wirelessly communicating with each other. Some may use other terms such as *embedded system*[9], *smart room*[11], and *sensor network*[5]. But in principle, it does not matter if the computers are fixed or migratable, situated in a room or outdoor. They all fall into the broader definition of ubiquitous computing, i.e., *computers in the environment*. By nature, ubiquitous computers have easy access to the resources in the environment, i.e., environment-centric resources. Wearable computers, on the other hand, mean computers that are with people all the time, i.e., *computers on people*. These computers have easy access to personal information, i.e., human-centric resources.

The wearable and ubiquitous computers, each class has its strength and weakness. It is often that one's weakness is the other's strength. That means ubiquitous and wearable computers can compliment each other, and applications adopting a combination of wearable and ubiquitous computers can take advantage of the both. This avoids the pitfall of putting much effort making one class work for all when in fact a much smaller amount of work is sufficient if cooperating the two. In general, applications involving interaction with the environment are better off introducing ubiquitous computers into the systems. Similarly, when interaction with people are involved, applications are better off using wearable computers.

Organization   We first review the wearable computer's history. Based on lessons learned, we project its potential existence in the future. To realize potential directions of future research, we survey relevant research in four areas, I/O interface, searching, communication and power. Then, we re-examine the motivation and address some speculations on the practicality of wearable computers. Finally, we propose exploratory projects aiming at developing suitable software-level communication solutions.

Figure 3: Left: A User Effortlessly Wearing the IBM Prototype. Right: Pieces of the IBM Prototype

2 Motivation

We found that wearable computers have quite a long history[16] – 732 years to be exact[3]. Recent proposals show a common trend on improving human abilities beyond our biological limits – so called cyborg applications[4]. Another historical trend is computers being smaller and increasingly accessible. If these trends continue, next generation computers are more likely to be worn around our waists and ready to compute anytime.

The first wearable computer [25] was revealed in 1966. It is a roulette wheel predictor. The idea started from 1955 when Ed Thorp was a second year graduate student at UCLA's physics department. In 1960, almost by accident, he described the idea of roulette wheel predictor to Claude Shannon, a mathematician at MIT. Soon the next year, the two built a wearable computer from scratch in Shannon's basement. It was a cigarette-pack sized analog computer with four buttons. The four buttons were used to indicate speed and the predicted results were transmitted by radio to an ear piece. Thorp and Shannon field-tested their wearable computer in Las Vegas and confirmed the expected gain of 44% obtained by laboratory experiments. Until the end of 1980s, most applications tend to stick to this gambling and gaming theme. However, there is gradually a noticeable amount of medical applications for the hearing and visually impaired. Then there came the blockbuster *Terminator* and the first commercialized head-mount display – *Private Eye* (Figure 5, left). The amount of proposals started to bloom in 90s. In the meantime, the theme made a sharp turn towards applications of daily and effortless use, in particular, augmented memory[17], location/context awareness[8], and very small computers[13] capable of running these applications. These proposals were, more or less, driven by the human desire to know (more, faster, anywhere and anytime). As Sir Bacon had nicely put it – knowledge is power.

Another trend we see from the general history of technology is the increasing *accessibility*. Take time computation for example. It has evolved from clock towers, wall clocks, pocket watches, to wristwatches. These time pieces get smaller and more accessible. With the wristwatches now, people can read time anywhere and anytime. Data computers has been following the same trend, evolving from mainframes, mini computers, desktop PCs, to laptops (some of them are really small). The next generation data computers are likely to be even more accessible and wearable, much as the wristwatches. If we think today that wristwatches are indispensable, perhaps one day we will think the same for wearable computers. Or many have already thought so if cellular phones qualify as wearable computers. Strictly speaking, we do not need wearable computers to survive, but like many technologies today they provide convenience and convenience is something difficult to resist.

Here, we conclude that from the history's point of view, human desire of knowledge and convenience

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[3]Eyeglasses were first mentioned in literature as early as 1268.

[4]According to the Merriam-Webster's collegiate dictionary, cyborgs are human having normal biological capability or performance enhanced by or as if by electronic or electro-mechanical devices.

Application
I/O
Communication
Heat	Power

Figure 4: Wearable Research Topics Divided into 5 Areas (going from software- to hardware-specific ones) : Application, I/O, Communication, Power and Heat.

is the hidden force behind the current wearable computer research. In Section 5, we argue the importance of pursuing wearable computer research further from the viewpoint of practicality.

3   State of Research

There are primarily five areas of research – I/O, searching, communication, power, and heat. Some of them deal with higher-level software issues whereas the others deal with lower-level hardware ones. Figure 4 shows their relationship in layers. We discuss these topics in a top-down fashion excluding heat, which is rather distant from the computer science and electrical engineering regimes. Example applications are given during the discussion of I/O interface and searching techniques primarily because technologies used are closely related to the nature of applications and mentioning of the applications helps highlight relevant I/O technologies.

3.1   I/O Interface

We have traditionally relied on text input devices such as keyboard, pointing device such as mouse, and output devices that sit about .5-1 meter away from users' eyes on desktop or laptop. Because of the hands-free and continuous use requirements, these I/O devices do not suit the use of wearable computers. In particular, traditional keyboards are to be operated with both hands. The scale of conventional desktop monitors or laptop LCD panels is too large to carry for a long time and too power consuming. To solve these problems, people have sought alternatives for conventional I/O devices and explore techniques in computer vision, graphics, and speech processing to enable I/O in visual and audio formats.

Input.   Solutions for input include one-hand keyboard with integrated mouse functionality, hand writing, video sensor, and speech processors. The integrated keyboard is expected to be used as the main input method and the rest as complimentary alternatives.

One immediate solution to replace the conventional keyboards and mouse is to re-arrange keys and to integrate the mouse functionality for one-hand operation. There exist a number of commercial products and lab prototypes. Twiddler[1] (Figure 2, right) is one of the most popular kinds. It consists of 6 function keys and 12 letter keys. The function keys are operated by the thumb. The letter keys are in 4 rows, 3 in each row and operated by one of the other 4 fingers respectively. Twiddler comes with drivers for Windows and Linux, as well as training programs. Some users have reported getting up to the speed of 10+ words per minute within a week[15]. Shortcuts can be pre-set to speed up frequent actions. Operating a Twiddler is pretty much like playing choruses on a guitar.

Hand-writing recognition is used in many palm-top devices. Some of them, e.g., Apple's Newton, recognize characters as they are written naturally, whereas others, e.g., 3Com's Palm Pilot, recognize characters in more cryptic patterns. While hand writing may appear as an intuitive input method, it does

Figure 5: Wearable Display: left picture shows a PrivateEye micro-display mounted on a glass; right picture shows state of the art integrated eyeglass display.

not work well for fast and bulk data input[20]. First of all, the recognition software can accommodate hand writing in various forms only to certain degree. For people who never really learn how to form the letters properly, this input method will not be a choice. Secondly, to write fast, people tend to scribble. The formations of letters get even worse and become very difficult, if possible, to recognize. Due to these two reasons, hand writing serves well as an alternative but will not be the primary input method.

Visual input is important to applications of more graphical nature. Physical profiles of an object such as size, shape, location, and movement are more direct and precise when obtained through camera-like input devices and analyzed by computer vision technologies. Take the Billiards Assistant[12] (Figure 6, left) for example. A head-mount camera takes a snapshot of the pool table. The computer vision part of the software identifies the white ball, the target ball and the pocket. These data are then fed into the angle calculation part for further processing.

Audio input is inevitable in situations that users' eyes and hands must engage in critical activities, e.g., driving a car. In these circumstances, audio is a nice, natural alternative to provoke simple commands. Microphones are typical audio input devices. They are often used together with speech processing technologies[19]. For instances, *speech recognition* translates analogous audio clips into digital forms that computers can understand or further process. *Speaker identification* helps identify persons or objects by their voice fingerprints. *Noise filtering* enhances the precision of speech recognition and has the potential of discovering context in the background[5].

Output. Solutions to output include head-mount displays with augmented reality and headphone for synthesized audio. The head-mount displays replace the relatively bulky monitors or LCD panels as primary output devices for wearables. Headphones are, on the other hand, a complimentary alternative.

In the wearable paradigm, hardware components tend to be small, so does the display. The next logical solution is to place *micro-displays* in the proximity of users' eyes. There exists a small number of commercialized products and most of the sophisticated ones, with full VGA capability, are still in development. More commonly used micro-displays are composed of 320x240 small pixels within a roughly 12 cm x 8 cm area (Figure **??**). More advanced ones use much smaller and four times more, 640x480, pixels that fits into a 1.2 cm x .8 cm area (Figure 2, left). These micro-displays can be mounted onto a hat, a glass, a helmet, or a custom-made head piece.

Current state of the art is rather a projector than a micro-monitor. The beamer is integrated into one leg of an eyeglass frame. Computer screen is projected onto a small area of the lens. See right picture of Figure 5. By that, users can see through the display and overlay virtual information with the reality[23]. In the Billiards Assistant example, the exact angle to hit the white ball is overlayed with the real white ball and pool table. This is assuming the users can hold their heads steady and the directions

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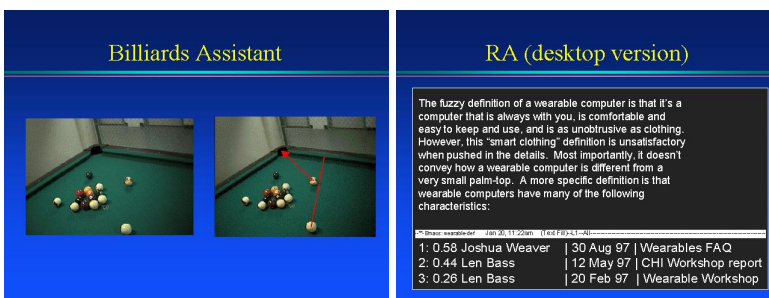[5]Users can be reminded of a train or bus coming while waiting and concentrating on a conversation.

Figure 6: Example Applications: left plot shows snapshots of the Billiard Assistant before and after angle calculation; right plot is a snapshot of the Remembrance Agent working with Emacs.

of eyeglasses and eye surfaces coincide completely. In practice, these two factors need to be taken into consideration and used to adjust results accordingly. For applications that require perception of depth, advanced computer graphics technologies, such as 2D-3D conversions, are necessary.

Audio output is preferable in situations that human eyes must be dedicated to more critical activities, similar to the reasons for audio input. *Speech synthesis* technologies will come in handy as solutions to generate comprehensible audio output.

3.2   Searching

There is a new class of applications unique to wearable computers. They work like personal assistants, handing documents upon request and proactively reminding us of relevant information[17]. Searching techniques are critical to this class of applications. Challenges mainly come from dealing with non-text documents and give *really* relevant reminders. The former problem is equivalent of how to index one's text, audio, and video archives for easy and fast search – field search. The latter problem is to imitate how one associates current context with memories – content match.

Existing Web searching engines work reasonably well with text-based documents. These searching engines are inadequate in the context of wearable computing where documents are commonly found in more 'cryptic' (or binary) formats – pdf texts, jpg images, and mpg video streams. Indexing and searching these documents poses a non-trivial challenge and is a emerging area of research. Most solutions adopt a 2-tier model. Non-text-based documents are first converted into text formats or smaller audio/video entities. Indexing and searching are done based on these converted texts or smaller entities.

Another desirable mode of searching is to match content and give relevant suggestions to users, much like recalling relevant experience in the memories.. Indexing and searching techniques in this context differ from those used in field searching. Whereas the field searching locates files with exact values in fields specified in the queries, the content matching mode tries to find similar files by matching a significantly wider range of contents. The content matching techniques often break a document into smaller elements, e.g., words, allocate weights to these elements, and compute the relevance combining simple heuristics and user-specified ratings.

MIT's Remembrance Agent[17] (Figure 6, right) implements both modes of searches – field- and content-based. The content matching uses a word vector approach. Each document is converted into a vector of unique, meaningful words with corresponding occurrence frequencies. This is referred to as the data vector. Same conversion is done on the text being edited at the moment and resulting in the query vector. They use a simple heuristic to calculate a document's relevance, which is basically a weighted sum of frequencies for words occurring in both the data and query vectors. Further technical details are provided in Section 4.2.
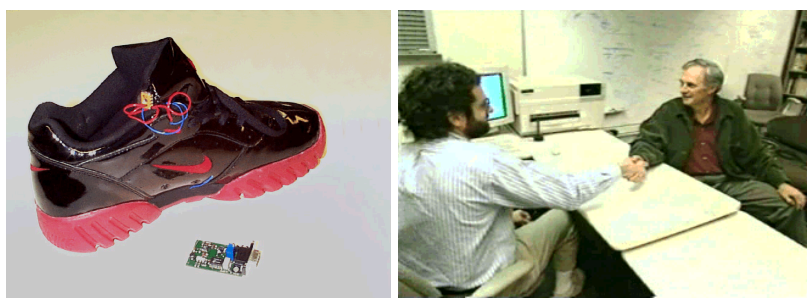
Figure 7: Body Area Network: left depicts the prototype as shoe insert; right depicts the Body Area Network working through hand shakes.

3.3 Communication

Communication for wearable computers includes communication between the wearable pieces, e.g., between the eye piece and the computing unit, and communication between the wearable computers to the rest of the world, e.g., between the wireless modem and an ISP dialup pool. We focus our discussion on the communication between wearable pieces, given that the communication between the wearable and the rest of the world is a more general and not specific to wearables. Communication between wearable pieces has a special set of requirements. Due to these requirements, suitable solutions are more likely to be found in short-range low-frequency wireless technologies. In this subsection, we discuss these requirements, review general wireless communication technologies, and finally present a plausible solution called *Body Area Network*[26].

In general, requirements for wearable communication tie back to the strict definition of wearable computer – continuous and intuitive use. For intuitive and easy use, wearable communication should be wireless. For continuous use, it needs to be energy efficient, which often means low frequency transmission. Additionally, due to the high confidentiality of data being communicated among the wearable pieces (often passwords and credit card numbers), it is desirable that the communication method comes with added security features. This usually implies that the wireless transmission needs to be short ranged so it has a lower probability of leaking information. The ultimate solution is to somehow wirelessly transmit signals through human bodies, which avoids leaking important information into the air at all. It is also desirable to reduce interference. However, interference is not specific to wearable communication. It is more a general problem that can be solved by signal attenuation and noise filtering techniques. In short, a wireless, low-frequency, body-range communication technology is preferable to network the pieces of a wearable computer.

Wireless communication technologies can be classified into two classes – far-field and near-field communications. Literally, technologies in the far-field class are more suitable for long ranged communication, and similarly those in the near-field class are for the short ranged communication. Typical *radio frequency* technologies fall into the far-field class whereas *Bluetooth*[7] loosely qualifies as a technology in the near-field class. To be more specific, a typical radio frequency antenna can read locations that are several hundred meters away. Bluetooth typically covers a region of about ten meter radius. The two classes of communications differ technically in signal degradation ratio and carrier requirement. In terms of signal degradation ratio, the far-field class is proportional to $1/d^2$, where d is the distance to signal source. The near-field class, on the other hand, is proportional to $1/d^3$. In terms of signal carrier requirement, for devices size of a watch or credit card, the far-field class requires carrier frequency in the scale of gigahertz while the near-field class requires carrier frequency in the scale of 0.1 to 1 megahertz.

For wearables, technologies in the near-field class that can cover the human range, roughly a three- to five-meter radius area, is preferable. AT&T Labs Cambridge's *Piconet*[3] is a very low frequency
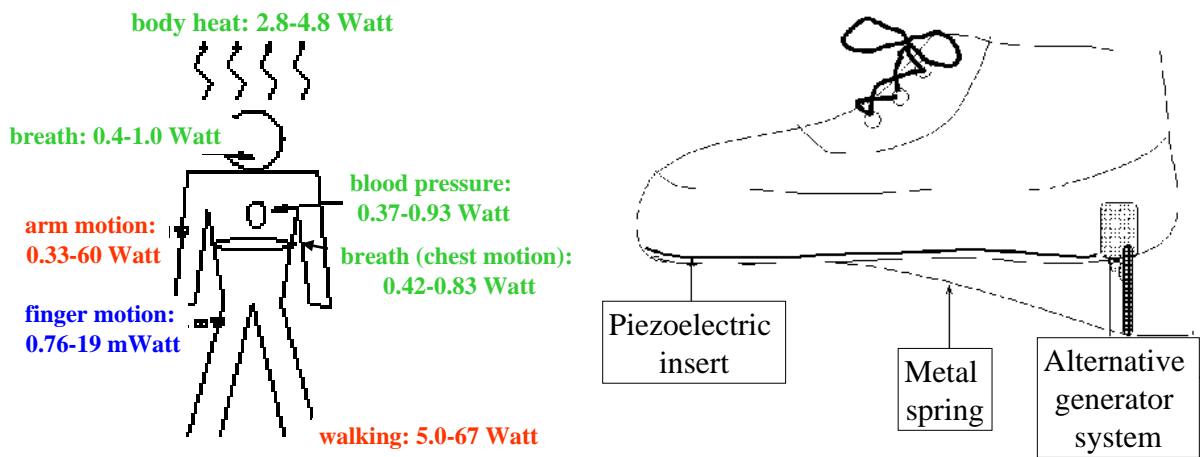
Figure 8: Human Power: left plot illustrates the theoretical potential of body movements; right plot demonstrates piezoelectric material and mechanical springs can be integrated into shoes to convert walking power.

radio network with roughly five meter range. Piconet meets the requirements of intuitive use and low power consumption. However, due to its radio transmission nature, it is still possible to leak out personal, confidential information in the air. Another promising solution is MIT Media Lab's Body Area Network[26]. Human bodies are used as wet conductor and take part in a circuit connecting a special transmitter, receiver and the earth. When the body is in a steady state, the circuit is balanced with zero potential. When the body moves, the resulting potential carries signals through the current[6].

It is measured that the carrier strength is 330 kilohertz and the power consumption is as little as 1.5 milliwatts[7]. Left picture of Figure 7 shows MIT's prototype as a shoe insert[14]. The prototype is tested with an application exchanging electronic business cards. Right picture of Figure 7 shows two people wearing the Body Area Network transceiver seamlessly exchange business cards by shaking hands.

3.4 Power

Power is essential to meet the criteria of continuous run. It also strongly influences a user's decision to use a wearable computer continuously. Unless the computer performs, there is no point of wearing one all the time. Batteries are the conventional solutions. They should be integrated into the wearable computers to provide the last layer of reliability in case that all other power sources fail. However, batteries should not be the sole power source given that wearable computers are supposed to be operated anywhere anytime, including hiking in mountains and standing in queue to get into the German embassy in Switzerland[8]. Next interesting question is how and where to get power. Because wearable computers are with people all the time, it is only natural to seek power generated by people. Below we evaluate the power requirements of wearable computers, provide theoretically figures on human potential, and finally look into some practical power solutions.

To understand better what types of power source are more practical, we first examine the average power consumption of the wearable computers. Traditional bigger wearable computers consume 5 watt

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[6]People must wear shoes to prevent short circuits.

[7]Body Area Network, however, utilizes a 30 volt power source.

[8]Oh yes, people have to arrive before 6:30 AM to make sure they have a chance to get into the visa office by 11:00 AM. From then, they can start worrying about convincing the embassy officials they should be granted a visa.

energy. A typical configuration includes a head mount display, 2 gigabyte hard disk, 133 megahertz Pentium CPU, and 20 megabyte RAM. More advanced wearable computers can consume as little as 0.7 watt power. This is possible by putting state of the art MicroOptical eyeglass display, flash memory, and StrongArm microprocessor (.3W at 115 MIPs) altogether. A power source that can continuously generate several watts of power is ideal.

According to a theoretical analysis [21], human energy in different forms, body heat, breathing, blood pressure, arm motion, finger motion, and walking, can generate power from milliwatts to several tens of watts. See left plot of Figure 8. Body heat can be converted into 2.8-4.8 watts energy. Blood pressure has the potential of 0.37-0.93 watts[9]. Breathing can generate energy in two ways – facial and chest motions by inhaling and exhaling. They can generate 0.4-1.0 and 0.42-0.83 watt power respectively. These three forms of energy sources do not require extra actions by the wearable users because people always dispense heat, breath, and have blood pressure.

The next three forms, however, require extra movements. Arm motion energy spans a wider range, from 0.33 to 60 watts. Given that we are more likely to type when using computers, finger motion can be an interesting alternative. Unfortunately, finger motions generate only about 0.76-19 milliwatts of power. The last energy form, walking, has the potential of generating minimum 5 watt to maximal 67 watt power.

All above figures are theoretically derived. Converting heat and blood pressure to reusable power is technologically difficult. Breathing and finger motion power is almost negligible. Arm motion and walking are both practical. However, walking is preferable for two reasons. The energy converting unit can be easily integrated as shoe inserts, and taking a walk looks much more natural than swinging arms for no obvious reasons.

There are two ways to transfer the power of walking into electricity. See right plot of Figure 8. One is to use piezoelectric materials that convert pressures of stepping into electrical energy. A 52 kilogram user can generate approximately 5 watts of power. The other is to use more traditional rotary generators that convert heel motions into electricity. The efficiency is determined by the distance of the spring system mounted in the heel, energy storage of the spring system, and the efficiency of the generator. The figure is about 12.5% which means .625 to 8.4 watts energy output. Together, a pair of shoes with both piezoelectric and spring inserts have a realistic potential of 11.25 to 26.8 watts electricity.

4   Applications

There are, in principle, six areas of applications for wearables – medicine, military, industrial training, education, entertainment, and daily use. Entertainment and medical applications were proposed early by designers in the pre-1990s (see Section 2). Among the medical applications, we select one remarkable case to discuss in depth. In this example, artificial vision, a wearable computer helped a blind patient see. During the early 90s, researchers felt more comfortable to exploit practical use of wearables in military, industrial training, and education areas. Since late 1990s, as wearable hardware getting matured, people proposed applications that are of daily use, for example, MIT's Remembrance Agent. In the following subsections, we provide technical details of the artificial vision and the Remembrance Agent work.

4.1   Artificial Vision

This research[4] is conducted by Institut Dobelle AG, Zurich and its branch Dobelle Institute Inc., in New York. By connecting a camera, a computer, an electrode array, and the brain's visual cortex, a

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[9]People having high blood pressure may generate more energy than others.

62-year-old blind patient, receiving the implant in 1978, can see again. See Figure 9.

The magic works in the following sequence. The camera mounted on the patient's eyeglass takes snapshots of the visual context. These image snapshots are sent to the wearable computer where edges of the objects are highlighted and if appropriate, re-colored to get better contrast. The processed images are sent to the array of 64 electrodes. The electrode array is, in a sense, a screen of 64 pixels, very low resolution. The electrodes then stimulate the visual cortex accordingly. Thus, the blind patient can see.

It is claimed that the blind patient has a vision of roughly 20/400 and can navigate around the experimental environment and, in a field test, New York subway stations. This artificial vision system does not work for all subjects. In reported successful case, the patient lost vision in one eye at 22, the other at 34, and received the implant at 41. The system failed for another patient losing vision at 5 and receiving implants at 40. In addition to the aspect of using a camera and computer to re-produce visual experience, the advance of medical and surgical techniques is as remarkable, especially running wires through skulls for 20 years without any infection.

4.2   Remembrance Agent

The Remembrance Agent (RA)[17] is developed by Bradley Rhodes as part of his thesis at MIT Media Lab. There are two major components, indexing and searching. The indexing part is programmed in C and can be executed independently daily. The searching part, in LISP, runs in the background of the emacs editor (Figure 6, right).

Two modes of searching are implemented – field searching and content matching. The field search is similar to existing database search. It is passive in a sense that users query documents with certain values in selected fields and then the search engines provide entries found in the database. The content matching is rather unique in a sense that it is proactive and adopts a *word vector* approach to compute *relevance* of documents to a fragment text being edited at the moment. When relevant documents are located, reminders show up in a small user-defined area in emacs. This proactive content matching emulates how users associate memories and helps users remember. Below we describe the details of the word vector matching technique, possible cooperation with sensors, and some practical experience.

Word vector matching works in two phases. The first phase is for the indexing program to generate the *word vector* per document, called *data vector* and when a text is edited, the content matching running in the background generates the *query vector*. The relevance is quantified and computed in the second phase as weights of the query vector in the data vector. The RA also accepts user ratings and takes both the user and heuristic weights into account.

The word vector is generated as follows. For each document or text fragment, words are sorted and their occurrences are counted. Common words such as 'the' and 'to' are removed. For the rest of 'meaningful' words, occurrence frequencies are calculated, thus forming a vector of unique words with frequencies, also referred to as weights. The relevance is quantified by a simple heuristic which sums up the weights of words in query vector with their weights in the data vector (equation 1).

$$Relevance = \sum_{w \in vector} QTW(w) \cdot DTW(w) \tag{1}$$

where QTW is the weight of w in the query vector and DTW is the weight of w in the data vector. QTW and DTW are not limited to one occurrence frequency metric. They can be developed into more complicated constructs to better capture the actual relevance.

One problem observed with the current RA release is in the indexing process. It is rather time consuming, approximately one hour for 15 megabytes of emails on a Pentium 75 megahertz, 16 megabyte RAM notebook, considered as a common configuration for wearables at the moment. It seems that even
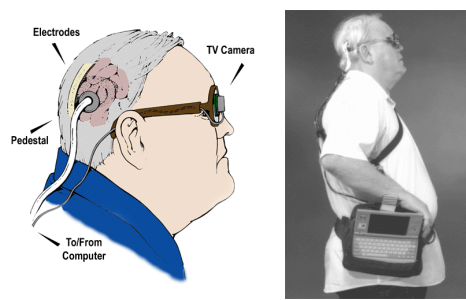
Figure 9: Artificial Vision: left figure shows interconnection of the camera, computer, electrodes, and visual cortex; right picture shows the subject wearing the artificial vision system.

though the RA avoids indexing binary files, ASCII postscripts, attached with the main mail content, slip in. When the postscript files are large, the indexing process uses a significantly large amount of memory, sometimes exceeding the physical RAM size and suffering badly from swapping. Postscript-specific, mostly meaningless, notations also challenge the word vector generation if they are not ignored properly in the process.

One important feature is that the Remembrance Agent can work with sensors embedded in the environment. Information of the surroundings (location and people) are noted automatically into the documents being edited at the time. The location and people information is used by the indexing program, and can be searched as a field or be part of the content matched in the proactive mode.

The Remembrance Agent has been used primarily by researchers. Reports suggest RA being useful in many cases, especially when preparing scientific papers. Users find related work section much easier to proceed because by the time the technical contents are completed, the RA would have suggested many relevant documents to review and persons to contact. It is often that call for papers also show up and suggest relevant conferences and journals to submit.

5   Discussion

Much of current debate is whether wearables will be useful, or used at all, in the future. In this section, we attempt to address some of the speculations and summarize the discussions. In general, we find that it is difficult to argue, for or against, if we will *need* wearable computers in the future like we need wristwatches today, or if there will be *a killer application* that people will be happy to buy wearable computers for. The reality could be any of the following cases:

- There is no need and no killer application at all.

- We have not discovered the need or killer application yet.

- We do not realize we already live in the need and there exist already many killer applications.

In any case, the industry should not invest much for widely deployment, because there is no apparent market[10]. or the market has already been taken. However, we as part of the research community have the responsibility to answer this question[11] – which case are we in? This prompts for more understanding to all aspects of the wearable computers, i.e.,

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[10]Typically, the industry waits for break-throughs in technologies, comes up with business models, and then deploys the technologies.

[11]After all, our mission, as researchers, is not to speculate but rather to provide answers.

- to what extend will the wearable computers be effortlessly operatable?

- to what extend will the wearable computers run continuously?

- to what extend will the wearable computer applications assist our daily lives, e.g., access to relevant information?

- to what extend will the wearable hardware and software together impact our lives?

Then, we might have a better picture whether wearables will be useful or necessary in the future. In the coming subsections, we highlight some of the questions raised and discussion followed.

5.1 Do We Really Need Wearable Computers?

One important question needs to be carefully examined is – do we need wearable computers? The short answer is – not now for daily life, but that does not preclude the need in medical use nowadays and potential daily use in the future. One thing we learned from the history is that there seems to be delicate dynamics between the society and technology. The society adapts to technologies; in the meantime, technologies adapt to the society. This forms an endless spiral. When looking back a couple cycles, present and necessary technologies are not really needed then. This supports the possibility of future need in wearable computers, and counter argues that technologies are not to be pursued if there is no present need.

Whether wearable computers will be really needed depends on how much convenience or productivity they have to offer. The reason is that usually people adapt only to useful technologies. When a significant amount of people adapt their lives to the technologies, the technologies become necessary. Thus, the question is really how much more convenience wearable computers can offer. Since services that are desirable now have higher chances of becoming necessary in the future, we check if these desirable services can be so much 'conveniently' provided by the wearable computers that people will be willing to adapt to the computers.

We find, in general, people desire these two services:

- to access information – voice, web, and location

- to find relevant information – searching, browsing, proactive reminders

Today, we have cellular phones for voice communication, WAP and wireless LAN technologies for data communication, and GPS transceivers for location awareness. These devices are quasi-wearable, i.e., they fit more or less in our pockets and can be carried around easily. It is not difficult to imagine after a few more cycles of Moore's Law taking effect, these devices' physical sizes and power consumption can be reduced to an extend that they actually meet the stricter definition of wearable computers and become affordable. Given the popularity of cellular phones and steady growth of GPS and wireless LAN user bases, it is very likely that we will need wearable computers in the future at least in the forms of cellular phones, and perhaps other wireless communication devices as well.

To get information on the Web, a WAP capable cellular phone might be sufficient. However, when people want other services not yet integrated or new services just introduced, they have to carry extra devices. It is cumbersome to carry them all and makes no sense to have a display and a keyboard per device. Besides, the fact that wearable computers being with people all the time suggests they can coordinate the numerous services to better suit users' life styles. Most wearable, or quasi wearable, devices today are highly heterogeneous and it is a very challenging task to coordinate them, sometimes impossible without software or hardware modification. Only when the services are more tightly coupled,

the coordination can be done more effectively. Concluding from the above, we think the existing devices will continue to be heterogeneous but plug-ins or modifications will slowly added to ease the burden of inter-operation. In the meantime, we also see more generic and flexible computers emerging as the central coordinating unit that can effortlessly, economically and effectively accommodate existing services and applications not foreseen. This breed of *coordinator computers* drives wearable hardware towards tiny, bare-boned, extendible computers with significant processing power[12].

Furthermore, as access technology advances, the amount of information available becomes intractable – so called information overflow. That increases the difficulty of pinpointing the information in need. We have actually experienced the information overflow problem once before when the World Wide Web bloomed. Most information providers, for example Yahoo and AltaVista, addressed the problem by crawling the Web overnight, indexing, classifying and organizing the information into a browsable directory and searchable database. We anticipate solutions for the wearables following a similar thread.

In spite of being useful already for the existing information services, we see great potentials of them working with another class of services – enhancing human abilities. That comes from the most valuable property of wearables being with users all the time. Such services already exist. Artificial vision (Section 4.1) helps blinds see. Sign language translators [24] helps deaf-mutes speak. Remembrance Agent (Section 4.2) helps people remember. If we continue to improve the wearable technologies, a life saver like this will be possible – calling an ambulance when a wearable computer detects signs of its owner getting a heart attack.

5.2   Is There a Killer Application?

Another interesting question is that 'is there an killer application?' We try to address this by giving example applications and see we can argue otherwise. Below are two instances of the debate. When hopping from seminars to seminars (or meetings to meetings), having a wearable computer that would tell exactly where to go next and what context to switch to can be helpful. However, it seems that simply asking others in the building and context switching during the seminars/meetings work too. Knowing exact location of a tram and easy access to the tram schedules will help make a decision whether to take another connection that might arrive earlier at the destination. However, Zurich city trams are punctual and the schedules are conveniently located by the tram stops. People of Zurich seem to cope with their busy schedules fine without such a tram network information system. It seems difficult to come up with an application that will impact a significant portion of our daily schedules.

This is perhaps just the way of life. We do a lot of little things or request little pieces of information everyday. When looked at one by one, each is small. But when a good deal of these daily tasks can be performed conveniently and ubiquitously at our fingertips, it will impact our lives. In other words, a collection of small applications can kill just as a single killer application can. Take Palm Pilot, which is gaining more and more popularity among business and computer professionals, for example. It provides a collection of personal organization utilities such as address book, calendar, email and flight schedule. Each of these application can be done otherwise without Palm Pilot, but when they are put together, the accumulated convenience attracts people to adapt to the technology.

6   Summary

We start this paper by re-visiting the concept of wearable computing and its complimentary duality with ubiquitous computing. After reviewing the history of relevant research, we sense the trend of wearable

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[12]These computers can be x86- or StrongArm-based.

Application
AI Techniques

Programming Interface

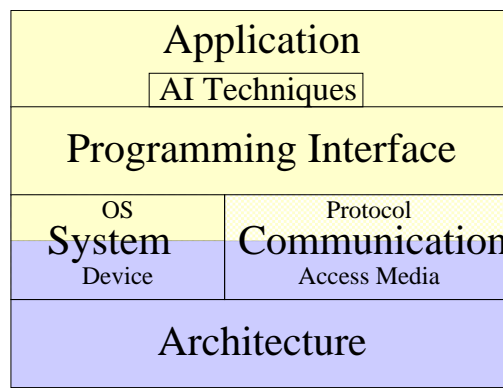| OS	Protocol
System	Communication
Device	Access Media

Architecture

Figure 10: High-Level Communication Protocol Design is the Area of Interest. Areas with darker shades are hardware-oriented and the lighter areas are software-oriented.

computing going towards daily and wider spread use. From there, we brain-storm about potential applications of daily use and rationalize desirable features. With a clear definition of wearable computer and specific goal in mind, we survey available technologies in four of the five relevant research areas, I/O interface, indexing and searching, communication and power. In conclusion, we find progress in research has pushed wearable technologies close to an ideal state, but not quite there yet. Much work is needed in three directions:

- hardware development,

- AI technique enhancement, and

- systematic performance evaluation.

In particular, the integrated one-hand keyboard and head-mount micro display are plausible I/O solutions, but related audio and video I/O techniques (computer vision and speech processing) do not seem robust enough for daily use. Communication-wised, Body Area Network and Piconet provide reasonable solutions. However, these proposals are more or less in the development stage and no formal evaluation has been done to compare their use for wearable computers. The power aspect is somewhat similar to communication. While piezoelectric and spring system inserts are promising solutions to convert the power of walking into electricity and to a level that 'continuous run' seems a reachable goal, no formal experiments are conducted to evaluate their efficiency with wearable computers.

After addressing some of the concerns about wearable computer's existence in the future, we decide to pursue studies in areas that existing technologies are inadequate, especially in the area of communication. In next section, we state our progressive goals and plans from acquiring wearable hardware to longer-term wearable-ubiquitous communication problems.

7 Exploratory Projects

As mentioned in Section 3, there are several areas of research, some more hardware-oriented and some more software-oriented. Our interest lies within the software-level communication issues (Figure 10). Typical problems are routing, scheduling, and end-to-end transporting (i.e., flow control and error recovery). To avoid the bitter lesson[13] with TCP, we think these communication issues should be pursued

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[13]People found TCP's window-based control is the source of many performance and fairness problems, so they proposed changes. Because the changes works well, partial deployment of them means unfair disadvantages to the old version users.

in the meantime applications and lower-level communication technologies are being developed. In other words, we need to learn more about the low-level communication characteristics and the environment and applications with which wearable computers are likely to operate. Our methodology is thus:

1. to select a target application that are useful in an academic environment (so we can conduct field tests).

2. to characterize usage and interaction with users, as well as the environment.

3. to understand the implication of different underlying communication technologies.

4. finally to devise plausible high-level communication solutions.

We intend to consult and collaborate with local expertise on relevant hardware (Prof. Troester), system (Prof. Mattern), and user interface (Prof. Schiele) issues. The overall plan gradually expends from communication among pieces of a wearable computer, communication between wearable computers, to communication between wearable and ubiquitous.

7.1   Wireless Cyborgs

A wearable computer usually consists of three components: input device, display, and computing unit. Considering the availability, quality, and cost, we select a one-hand integrated keyboard as the input, a head-mount display as the display, and a sub-notebook as the central computing unit. In this first project, we seek to replace communication wires with wireless technologies. We hope that during the process of experimenting with various wireless technologies, we learn more about the potential impact of low-level wireless technologies may have to higher-levels communication protocols. After the wearable pieces are successfully un-wired, we then switch our emphasis to characterizing the usage, loss, and possible interference. Based on these findings, we aim to design suitable transport protocols for the intra-wearable network. Below is a detailed, step-by-step plan.

1. acquire a one-hand keyboard and head-mount display

2. un-wire the one-hand keyboard with various near-field wireless communication technologies, e.g., IrDA[2], Piconet[3], and Body Area Network[26]

3. un-wire the head-mount display with various near-field wireless communication technologies

4. distinguish signals keyboard-to-computer from computer-to-display

5. characterize usage, loss and interference

6. validate usage, loss and interference models with longer-term field tests.

7. design transport protocols for inter-keyboard-computer and inter-computer-display communication

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Users will jump and so we are stuck in a local maximum.

7.2 Seamless Business Card Exchange

To understand relevant inter-wearable communication problems, we propose an application that allows seamless business card exchanges among PC, Palm Pilot and cellular phones. Each exchange will be done between a wearable PC and another wearable device by existing technology, e.g., a cellular phone or Palm Pilot in the following logical flow:

1. A wearable PC listens to signals from its peer wearable device and distinguishes them – a Palm Pilot or cellular phone of certain brand and model.

2. The wearable PC sends the corresponding business card exchanging program.

3. Upon reception, the peer device executes the program.

4. The program inserts a new address/phone book entry and sends back information about the peer device owner – thus completing exchanging business cards electronically.

Our approach to identify appropriate solutions for inter-wearable communication will be similar to the one described in the first project. One exception is that we intend to include two more wireless communication technologies, Bluetooth[7] and wireless LAN[10], in our evaluation.

7.3 Personnel Map

To understand relevant inter-wearable-ubiquitous communication problems, we propose an application that provides maps of personnel wearing computers in locations equipped with sensors. We seek to strategically place sensors at the critical points in a building. These sensors receive signals from office members' wearable devices and sends aggregated reports to the map generation server (a computer with more processing power). The wearable devices here can be very small PCs, Palm Pilots, cellular phones, as well as ETH cards with smart tags. Programming work involved includes:

1. identification announcement daemon for the wearable devices

2. identification announcement receiver and report sender for the sensors

3. personnel map generator and user visualization front-end as an auto-reload web page for the map server

We then adopt the same approach as in the first two projects to devise appropriate solutions for inter-wearable-ubiquitous communication.

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