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WEARABLE COMPUTING: Retrospectives on the first decade

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When I started at Carnegie Mellon University (CMU) in 1972, I joined Gordon Bell's research group just as he started to explore multiprocessor systems. Later in 1972, Sam Fuller joined the research group and the Computer Module project was born. Cm* (Computer module replicated one or more times as indicated by the Kline star) was an extensible architecture with shared address space across a local bus, extending to a cluster bus, and to intercluster links realizing the first non-uniform memory access (NUMA) multiprocessor [18]. By the end of the 1970s, industry became very interested in multiprocessor systems and it became difficult for university design teams primarily composed of students to keep pace with professional engineering teams with more resources in designing higher speed and ever more complex logic.

In the 1980s, we switched our focus to developing computer aided design with a goal of synthesizing a single board computer in less than 24 hours. By the late 1980s, the Micon system [2] could take about twenty high-level specifications similar to what was on the back of a product brochure (microprocessor instruction set, processor speed, amount of memory, number and type of input/output ports, board area, power, reliability, cost…) and generate a parts list and net list in less than ten minutes. A further optimization phase of ten minutes could reduce the cost, power consumption, and failure rate by a factor of two to four. We synthesized a simple single board computer to demonstrate that Micon could produce viable designs. After the first success, we sought a further, more challenging example.

During the fall of 1990, we were planning a ten-week summer course on design for industrial executives. Rather than lecture for ten weeks, we thought it would be good to augment the lectures with afternoon hands-on laboratories so they could experience design. A team from Electrical Engineering, Computer Science, and Design from the College of Fine Arts decided on a wearable computer with the computer hardware equivalent to a second generation IBM PC-AT synthesized by Micon and a housing designed with blue foam and implemented with vacuum forming of plastic. Addition of the newly introduced Private Eye Head Mounted Display completed the design. Blueprints for a house were implemented and could be scrolled left-right and up-down, thus demonstrating taking technical material to a work site. The summer students dubbed the system Vu-Man. Thirty Vu-Man 1s (Figure 1a) were fabricated and everyone in the course signed the inside of the housing and had one to take home.

We started showing VuMan 1 as an example of the synthesis power of the Micon system. Everyone was more interested in the potential of the wearable computer and made suggestions on new applications. Wearable computers were an ideal academic research project since the hardware was buildable by students and industry was not yet interested in an unproven business model [1, 4, 22]. Thus was born our decade-long exploration of the wearable computer design space [16, 17].

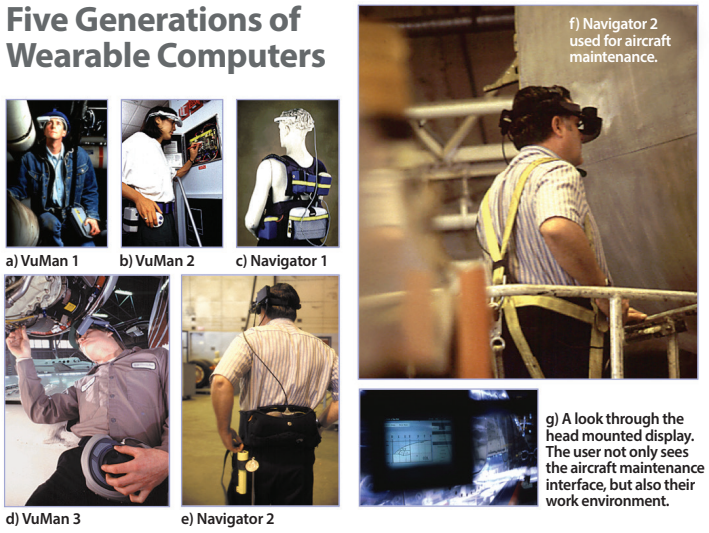


FIGURE 1. Five Generations of Wearable Computers

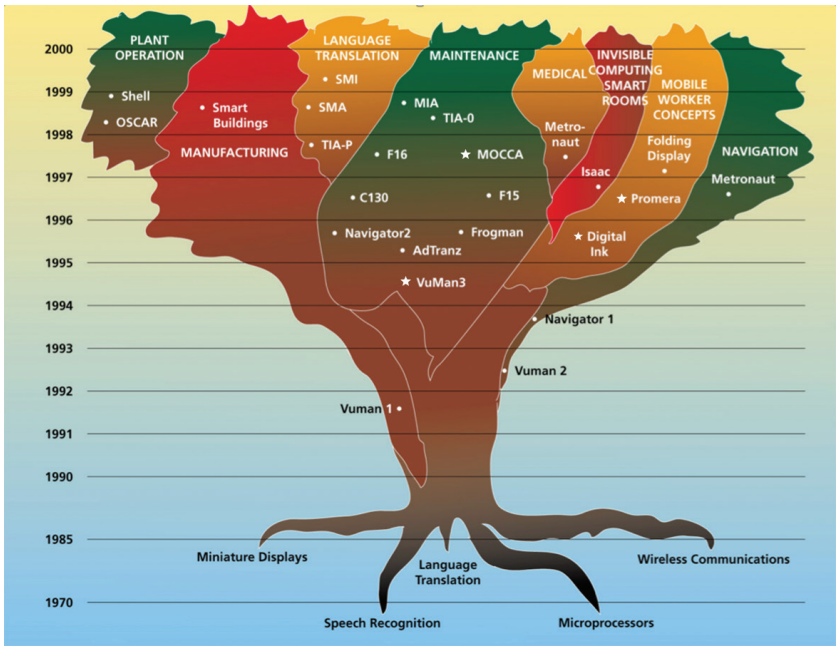


FIGURE 2. The Wearable Group's family tree of systems.

The Team: The wearable computer group created on average three new systems per year for a decade representing more than 100 person years of experience. Such productivity requires a dedicated multidisciplinary team with expertise in Design, Computer Engineering, Computer Science, Human Computer Interaction, and Management. The results of the research were spread through people. Numerous personnel that came through the program started companies and worked on products that laid the foundation of today's wearable technology industry.

Chris Kasabach, John "Ivo" Stivoric, and Francine Gemperle from Design in the College of Fine Arts contributed ideas on form factors, wearability, and fashion. Computer engineers Randy Casciola and Drew Anderson designed and fabricated

many of the printed circuit boards. Especially significant contributions came from Jane Segal in HCI, who designed and secured Institutional Review Board (IRB) approval for evaluation of our systems by end users during their normal work activities. In the management team, Dick Martin, former commissioning captain of the Carl Vinson nuclear aircraft carrier, was crucial in providing insights into how to work with the military clients as well as organizing field evaluations. Asim Smailagic became an extraordinary student mentor and our expert for language translators that were deployed to Bosnia.

Along the way, there were several commercial spinoffs, including BodyMedia in 1997 with Chris and John on the co-founding team, becoming one of the first companies to commercially offer wearable sensors (eventually acquired by Jawbone), Morewood Labs founded by Randy and Drew that designed electronics for the first five models of wearables from FitBit, and ESI with Dick and Dan among the co-founders that was a forerunner to Inmedius, which developed tools for authoring Interactive Electronic Technical Manuals (IETMs) for F-18 maintenance worldwide (eventually acquired by Boeing).

The Community: By 1995, a community of wearable researchers was forming. Boeing hosted a workshop in 1996. By 1997, an IEEE Working Group on Wearable Information Systems (WIS) was formed and organized the First International Symposium on Wearable Computers (ISWC) at MIT with Thad Starner as general chair. By 1998 the Working Group had been promoted to a Technical Committee that I chaired and the second ISWC was held in 1998 hosted by CMU. ISWC has been held annually ever since.

THE EVOLUTION OF CMU WEARABLE COMPUTERS

The Family Tree of CMU Wearable Computers, as shown in Figure 2, classifies wearable computers into several application categories and presents their development over the decade of the 1990s. The tree is modeled after the NSF "Family Tree" of early computers circa 1955. Each name represents a distinct wearable computer placed under its corresponding application domain. The four wearable computer designs marked with a star have been awarded prestigious international design awards (VuMan 3, MoCCA [19], Digital Ink [7], and Promera).

TABLE 1. Visionary Design and Research Studies

Name	Year	Goal/Concept
Digital Ink	1996	Pen Computer, IDEA Award
Promera	1997	Hand held camera/projector
Folio	1997	Foldable display
Design for Wearability	1998	Research into wearable shapes and body positions
Streetware	1998	Fashionable computer
Sprout	2000	Wireless communications
Tactile Display	2001	Exploring User Interactions

TABLE 2. Exploring/System Design

Name	Year	Application	Number Built	Special Attributes
VuMan 1	1991	Blueprint display	30	2 pound, 4 W PC AT
VuMan 2	1992	Navigation Assistant	6	0.5 pounds, 1 W
Navigator 1	1993	Navigation Assistant	4	GPS, cell phone, speech recognition
Frogman	1996	Maintenance	1	Waterproof, fabricated by 3D printing
Issac	1997	Smart Room	1	Speech control
Metranaut	1997	Navigation/ information/medical	1	Two-way pager
TIA-0	1998	Maintenance	4	Integrated, compact design
Itsy/Cue	1999	Low power, wireless communication	6	Forerunner to HP iPaq and smart phone
Smart modules	1999	SM0, SM1 research platforms	6	Modules for speech recognition, translation, and synthesis
Spot	2001	Research platform	4	High-fidelity graphics

Wearable computers at Carnegie Mellon have ranged from Visionary Design and Research Studies (Table 1) to Exploring System Design (Table 2) to Customer Driven Systems Design (Table 3). We built wearable computers for more than a dozen clients with a focus on industrial applications. [3] At their inception, head-mounted displays cost several thousand dollars. But industry could afford the equipment cost through improved productivity. We built many systems to explore the application design space looking for repeated patterns. Much like word processing, spreadsheet, and power point slides were applications that made the personal computer so effective, we found applications that recurred in mobile computing: procedures, work orders, and collaboration.

Procedures: Maintenance and plant operation applications are characterized by a large volume of information that varies slowly over time. [3] A typical request consists of approximately ten pages of text and schematic drawings. Changes to the centralized information base can occur on a weekly basis. For example, even simple aircraft may have over a hundred thousand

manual pages. But due to operational changes and upgrades, half of these pages are obsolete every six months for even very mature aircraft. Maintenance facilities usually have a centralized data base to which maintenance personnel make inquiries for the relevant manual sections on demand. The results (such as inspection) are uploaded at the end of the procedure. Procedures were explored by VuMan 3 (Figure 1d), Navigator 2 (Figures 1e, 1f, and 1g), TIA-P (F-15), MIA [14], OSCAR, and Shell.

Work Orders: The trend is towards more customization in systems. When personnel carrying out manufacturing or scheduled maintenance arrive for a day's work, they receive a list of job orders that describe the tasks and include documentation such as text and schematic drawings. This information can change on a daily or even hourly basis. Work orders were explored by Electric Boat, TIA-P (F-16), IBM Wearable (F-18).

Collaboration: An individual often requires assistance. In a "Help Desk," an experienced person is contacted for audio and visual assistance. The Help Desk can service many people simultaneously. Information can change on a minute-by-minute and sometimes even a second-by-second basis. Today, with downsizing and productivity improvement goals, teams of people are geographically distributed yet are expected to pool their knowledge to solve immediate problems. An extension of Help Desk is a team of personnel such as field service engineers, police and firefighters, who are joining together to resolve an emergency situation. Collaboration was explored by Adtranz [20], TIA-P (C-130), and MoCCA [19].

TABLE 3 Customer-Driven System Design

Name	Year	Application	Number Built	Deployment
VuMan 3	1994	Heavy vehicle inspection	10	Marine Base, Camp Pendleton, CA
Navigator 2	1995	Aircraft sheet metal inspection	6	McClellan AFB, Sacramento, CA
Adtranz	1995	People Mover maintenance	1	Pittsburgh International Airport
TIA-P	1996	English to Serbo-Croatian Language Translation	8	NATO Troops, Bosnia
		F-15 Inspection and maintenance	6	Warner Robins AFB, Georgia
		C-130 Help Desk	4	Air National Guard, Pittsburgh International Airport
		F-16 maintenance	4	Wright Patterson AFB, Dayton Ohio
Electric Boat	1997	Structural welding of nuclear submarines	1	Electric Boat, Groton Connecticut
MIA	1997	Bridge inspection	1	Pennsylvania Department of Transportation
OSCAR	1998	Offshore oil platform crane operation	1	Gulf Coast, Louisiana
Shell	1998	Offshore oil platform operations with intrinsically safe electonics	4	North Sea
MoCCA	1999	Mobile team-based maintenance	4	Digital Equipment Corporation
IBM Wearable	2000	F-18 Aircraft Maintenance	4	China Lake, CA

UCAMP

We summarized many of our lessons learned into an acronym UCAMP for User, Corporal (physically interfacing without discomfort or distraction), Attention (divided between physical and virtual world), Manipulation (controls quick to find and easy to operate), and Power. [21].

User Lessons: The Human Computer Interaction Institute (HCII) at Carnegie Mellon University has a mantra – "The User is not I" meaning that we need to work directly with the final users of the system to understand their work and how technology can assist. Engineers, computer scientists, and students are very comfortable with computer technology and may overlook something that seems obvious to them but may be a complete mystery to laity. We integrate end users into the design team at the very beginning. Building over a dozen user-driven systems allowed us to identify repeated patterns.

Mobile users are more impatient than desktop users. While holding a heavy object or when it is cold outside, three minutes is an intolerably long time to wait while an operating system boots up. The system must operate more like a flashlight with a very brief turn-on delay.

Most wearable system evaluation involves humans that are protected by an Institutional Review Board (IRB). Systems evaluations have to carefully design protocols with the option for users to drop out of the study for any reason without penalty. We even had Marines, who are accustomed to following orders, sign IRB informed consent forms.

Be prepared to reduce functionality. The initial visionary scenario may contain too many or infrequently used features that complicate an intuitive interaction model.

It is important to have someone on the design team that can relate to the end user and their culture. This provides the design team with instant creditability so end users will listen, provide suggestions, and accept the technology. Often the creditability comes from an end user of the target group. Finding that first end user to be a member

of the design team takes skill. Since many of our systems involved military applications, a key member of our core team who often found our first end user was Dick Martin.

Corporal Lessons: The systems should be easy to physically interface to without discomfort or distraction. We developed Navigator 2 for aircraft sheet metal inspection. It was mounted in the small of the user's back (Figure 1e). We had a trial on KC-135 refueling tankers at the Air Logistics Command in Sacramento, CA, on a hot August day. Even though they were only consuming two watts with a footprint less than a square foot, users of Navigator 2 complained of discomfort. The wearable computer acted as a vapor barrier and prevented the user's body from evaporative cooling by sweating.

When giving a demonstration, be sure to complete the demonstration before anyone else can touch the equipment. We had a demonstration at Fort Gorden Battle Command in Georgia. We were using PCMCIA memory cards for our software. The head of the unit took the PCMCIA card and warped it, saying, "Does this bend? Too many times equipment is released to the field and can not withstand physical handling." We had never tested the PCMCIA card in that manner – fortunately the card still worked and we could give the demonstration.

We prepared English to Serbo-Croatian TIA-P units for NATO troops to use in Bosnia. We picked a heavy-duty industrial-strength housing and screen that could survive eight-foot drops onto concrete. We sent six units to Bosnia – parts of one were returned. The lesson is never to underestimate the harshness of the end user's environment.

Attention Lessons: An example of divided attention we see every day occurs when someone using a smartphone walks into a physical object, such as a tree or telephone pole. It is much more serious when a driver talking on a cell phone goes through a red light at a busy intersection. The more information provided in and the more engaging the virtual world, the less the user will interact with the physical world. Thus we designed our systems to be used for reference (e.g., information dashboard) allowing the user to focus on the physical world.

SEVERAL CHALLENGES REMAIN. FOR INSTANCE, WHEN AND HOW SHOULD A WEARABLE COMPUTER INTERRUPT A USER?

Manipulation Lessons: The goal is to design controls that are quick to find and easy to operate. We relied on a strong user interaction mental model. For example, VuMan 3 (Figure 3) had a dial that could be rotated in either direction. As the dial was turned, the "clickable" items on the screen were highlighted and progression from one item to the next was in a circle. The dial and circular arrangement of clickable points provided a graphic and easy-to-understand relationship. This allowed not only for training in the field in less than ten minutes but also the ability of the trainee to train the next user. In addition, the trainer had to instruct without access to what the user is seeing. Another goal is for the interaction to be so intuitive that a user manual would not be necessary.

It is important that the manipulation be used without a reference position (Figure 3). Without stationary reference, mobile users become disoriented easily and confused with traditional input devices. For example, a desktop mouse has a top side and a left side. But if you are holding a mouse in your hand, how do you tell which is the left button – is it with the bottom facing the ground, with the cord pointing towards the body? [15].

Control devices also have to be flexible to mount on different parts of the body (Figures 1d and 4). Aircraft workers have to squeeze into tight places and do not want anything to add diameter to their waist dimension. Sailors on aircraft carriers use their shoulders to carry tie-down chains.

Power Lessons. For mobile electronics that have low duty cycles but high demands when activated, it's the peak power demand that determines battery capacity not the average. [8, 9, 10, 11]. In our early systems, we overdrew the batteries and after continuous use the internal battery resistance heated the electrolyte creating a vapor that burst the battery shell allowing the electrolyte to escape into the electronics.

The power system should be designed as foolproof as possible. Warning labels are no substitute for good design. During our field



FIGURE 3. VuMan 3.



FIGURE 4. AMEC technician selecting next step in procedure.

trial with Navigator 2, we had not completed the turn off charging circuit, so we placed a warning label "Do not charge overnight." Of course, on the first night, the unit was overcharged breaching the battery cases and spilling electrolyte over all the electronics.

There is more to gain on reducing power demand than increasing the power source. Current batteries have half of the energy density of dynamite. Unfortunately, current design of user interactions demand all resources to reduce response time. However, knowledge of the application can be used to reduce computational demand. For example, experiments with the eWatch [23] showed that sampling accelerometers at six Hz yielded the same classification accuracy for activities (running, walking, standing, sitting) as sampling with the standard 20 Hz. Once an activity commences, it is likely to continue for minutes or longer, allowing the electronics to enter a deep sleep and improving battery life by a factor of three at

the cost of additional latency at recognizing an activity change [6, 12].

It is important to standardize on an energy source form factor. The Land Warrior system [13] required nine different battery types complicating logistics and the weight that soldiers had to carry.

GUIDELINES FOR BUILDING WEARABLE SYSTEMS

Based upon our experiences, we conclude by providing guidelines for building wearable systems. There is a maximum size, weight, and energy consumption before the system causes the user to change their behavior. [5] When mobile, there is no fixed relationship between input/output/display. Mobile users are less patient and expect an instant response. Mobile systems should be intuitive to use with no user manual. Be careful not to create information overload, in which a user may focus on the computer rather than the physical world. There is a potential for the user to lose initiative, doing exactly what the computer tells them to do. The system should fit into current procedures/logistics. Be aware of environmental influences and their impact on the system. Finally, be especially aware of power consumption and battery characteristics.

RESEARCH CHALLENGES

Several research challenges remain. We need to determine when and how the wearable computer should interrupt a user, balancing need versus disruption. How should user attention be valued? Should the concept of an attention market be developed, combining theories from social science, cognitive science, and economics?

For data privacy, we need to determine what data we should allow a wearable computer to collect. Who should have access to this data? How does the user specify their preferences on availability of the data? And how long should the data be retained? ■

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