Very Rapid Prototyping of Wearable Computers: A Case Study of Custom Versus Off-the-Shelf Design Methodologies

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Abstract*

The Wearable Computer Project is a testbed integrating research on rapid design and prototyping. Based on representative examples from six generations of wearable computers, the paper focuses on the differences in rapid prototyping using custom design versus off-the-shelf components. The attributes characterizing these two design styles are defined and illustrated by experimental measurements. The off-the-shelf approach required ten times the overhead, 30% more cost, fifty times the storage resources, 20% more effort, live times more power, but 30% less effort to port software than the embedded approach.

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1 Introduction

Exponential advances in technology require rapid prototyping as an essential aspect of design and manufacturing. Competitiveness in the global economy requires rapid response to changing market demands, as well as capturing rapid technological advances and translating them into new products. Rapid prototyping is an example of a group of CAD/CAM methodologies which shorten the design/manufacturing cycle. There is no single rapid prototyping technology which addresses all the challenges posed by product development. Success requires innovation and incorporation of a broad range of technologies covering scale (micro to macro), domains (electrical, mechanical, software), media (physical and virtual) and resources (local and distributed). Carnegie Mellon University has addressed many of these issues in research on rapid prototyping of electronic/ mechanical systems.

This paper illustrates how the Engineering Design Research Center is using the wearable computer project as a testbed in which to perform research on rapid design and prototyping. Through this process we have learned about rapid prototyping education and practice. Based on representative examples from six generations of wearable computers, the paper focuses on rapid prototyping of custom designed vs. off-the-shelf systems. As running examples we will use the Navigator 1 general purpose wearable computer and the VuMan 3 custom designed wearable computer, as these two computers are comparable in functionality. In the next section we will present the characteristics of Navigator 1 and VuMan 3 wearable computers.

2 Case Study: Navigator 1 and VuMan 3 Wearable Computers

Carnegie Mellon University has rapidly designed and prototyped six generations of wearable computers: VuMan i [1], VuMan 2 [2], Navigator 1 [3], VuMan MA [4], VuMan 3, and Navigator 2. These generations of wearable computers could be classified into two generic classes of systems: custom designed (VuMan) and designed by composition systems (Navigator), using mainly off-the-shelf components. In addition to custom designed electronics and mechanical enclosure/ interface, VuMan wearable computers have also adopted an embedded, custom-designed approach to the software information system. In Navigator, a modular "mix-and-match" architecture allows multiple configurations increasing the general purpose nature of the wearable computer. Figure 1 presents the main characteristics of the CMU wearable computers.

An Interdisciplinary Concurrent Design Methodology (ICDM) [3], [5], [6] has been evolving, as we design new artifacts and processes. The goal of the design methodology is to allow as much concurrency as possible in the design process. Concurrency is sought in both time and resources. Time is divided into phases. Activities within a phase proceed in parallel but are synchronized at phase boundaries. Resources consist of personnel, hardware platforms and communications. Personnel resources are dynamically allocated to groups that focus on specific problems. As a result of this methodology, we have achieved a four months design cycle for each new generation of wearable computers. The cycle time of the new products is ideally suited to the academic

E V O L U T I O N

Characteristics and Attributes of EDRC Wearable Computers

Vu Man

Vu Man 2

Navigator

Vu Man 3

Navigator 2

Artifact Specifications	Vu Man 1	Vu Man 2	Navigator 1	Vu Man 3	Navigator 2
Delivery Date	Aug91	Dec 92	June 93	Dec 94	!uk/95
Number of units	30	6	3	20	8
Embedded/GP	embedded	embedded	general purpose	embedded	general purpose
Design Style	semrcustom	fullycustom	design by composition	fullycustom	semhcuslom
# of custom boards/chip count	1/24	1/5	3/15	2/10	2/29
# of off-theshelf boards	1	0	5	0	2
lines of code	1800	4700	38000	12000	88000
Processor	80188 -8MHz	8OC188-13MHz	80386-25 AAHz	80386EX-20MH2	486SX-33+DSP
RAM/Nonvolatile storage	8KB-512KB	512KB - 1MB	16MB - 85MB	1 MB - 420MB	12MB - 420MB
Input	3-button	3-button	speech/mouse	rotary w/button	speech / joystick
Display resoiution	720x280	720x280	720x280	720x280	640x480
Dimensions (inches)	10.5x5.25x3	4.75x4.5x1.37	7.25x10x3	5x6.25x2	5.8x10.7x3.2
Power (W)	3.8	1.1	*7.5*	2	7.5
Weight (lbs)	3.3	0.5	9	1.75	4

Artifact Sp^ificationr					
Magnitude of Design Activity:	innovative	innovative	innovative	innovative	innovative
(a) No. Designers	4	6	21	16	23
(b) No. CAD Took	16	16	7	7	8
(c) PersonMo. Effort	12	6	28	23	33
Quantity of Artifacts Fabricated	30	6	3	20	8
(a) Electronic Part Count	45	12	8 boards	2 boards	2 boards
(b) Housing Fabrication	vacuumforrr.ing	SIA / molding	pressure forming	molding / machining	molding / machining

Table 1

semester. Figure 2 illustrates the iterative nature of user centered design to elicit feedback during the design cycle. Student designers initially visit the user site for a walk-through of the intended application. A second visit after a month of design elicits responses to story boards of the use of the artifact and the information content on the computer screen. After the second month a software mock-up of the system running on a previous generation wearable computer is evaluated in the end-user's application. During the third month, a prototype of the system receives a further user critique. The final system is delivered after the fourth month for field trial evaluation.

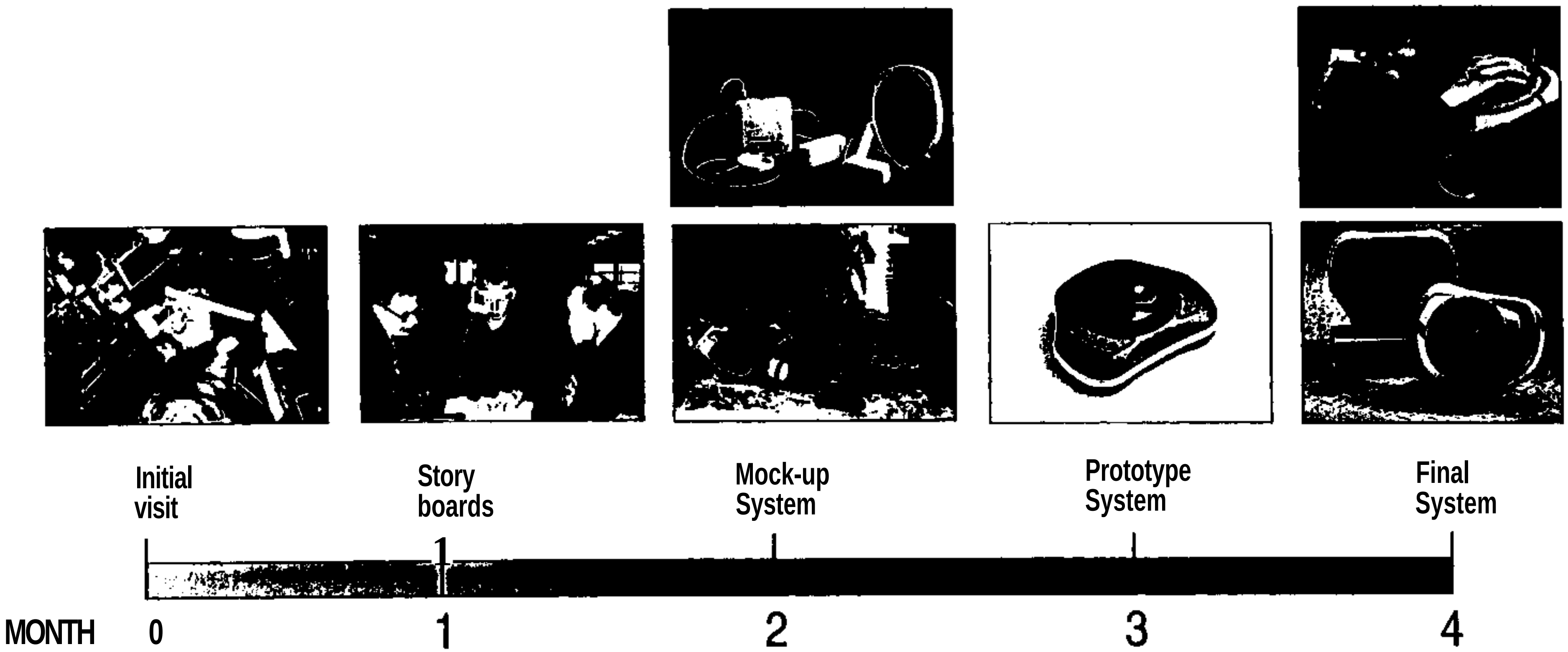
Based on representative examples from these six generations of wearable computers, we have observed a clear impact that the design style (custom vs. off-the-shelf) has on the cost and efficiency of our rapid design/prototyping process. The major attributes are the following:

- **Overhead factor**
- **Relative cost**
- **Personpower**
- **Software portability**
- **Power management**
- **Storage requirements**

These attributes are defined in the next section. As running examples we will use the Navigator 1 general purpose wearable computer and the VuMan 3 custom designed wearable computer. Their major characteristics are summarized in Figure I.

Navigator 1, built in 1993, is a general purpose computer consisting of off-the-shelf boards: an 386SX processor card. Private Eye interface [7], VGA controller, A/D card, GPS (global position sensing) card, modem, disk, and mouse controller. The custom boards in Navigator include the GPS interface, on-set of speech detection, and power control. The initial application was campus navigation. Navigator can use speech as input, allowing completely hands-free operation. Navigator 1 's speech recognition system is speaker-independent [8], has a 200 word vocabulary, and runs at about eight times real time. A mouse is also available, in case that speech is undesirable. Navigator 1 runs the Mach operating system [9], allowing applications to be developed on a Unix workstation and then transferred to the Navigator 1 platform. Software developers can use the standard Unix environment, such as X Windows [10] and Shell scripts, in their applications. Modularity of design was a very important concern. Navigator 1 is composed of modular subsystems, such as head-mounted display, global position sensing (GPS), and telecommunication. A study of the Navigator 1 produced a set of techniques that reduced the power consumption of the off-the-shelf boards by 50% [11].

VuMan 3. built in 1995, is a fully custom design. The initial VuMan 3 application is as a wearable maintenance assistant, allowing users to display and interact with reference manuals in the form of hypertext documents. The user centered design process involved tight interaction with the intended users, the U.S. Marines. VuMan 3 includes an Intel 386EX processor with on-chip integrated power management, and two DMA channels; programmable microcontrollers for input/output (allowing reconfiguration with mouse, dial, or joystick); and power control selectively turning off unused chips; a second printed circuit board supports a PCMCIA controller with two slots; and a



Four Month Design Cycle

novel rotary dial input device.

VuMan 3 provides modularity via PCMCIA card options. A new forms based VuMan Hyptertext Language (VHTL) was the basis of the application software and user interface implementation. VuMan 3 also supports the campus navigation application. The campus navigation application is common to both Navigator 1 and VuMan 3 and will be used to compare the two systems.

3 Evaluation of the two Design Styles

We will now evaluate the impact of the two design styles on six major design attributes.

3.1 Overhead Factor

The overhead factor is defined as

(number of features available - number of features used)/number of features available , {1)

Table I lists the specifications and major features of the off-the-shelf boards used in Navigator 1, and illustrates the mismatch of requirements between desktop and mobile hardware [8]. The design was meant to be a proof of concept, so off-the-shelf boards were used to minimize electronic design time and the probability of electronic design errors. Only one of the off-the-shelf boards, the CPU motherboard, was designed for mobile use. The analog-to-digital (A/D) conversion board and the Private Eye board were intended for use in desktop PCs. Neither of these boards were designed with mobility or power consumption in mind.

Table 2 shows the specifications and major feature of the three custom designed boards in \0Man 3: main processor board, the PCMCIA controller board, and the docking station board, which acts as an input/output processor. A smart docking station monitors the use of the NiCd rechargeable batteries and also acts as a communication link to a logistic computer system, in order to upload the inspection data. Using the data in Table 1 and equation 1 the overhead factor for Navigator 1 is calculated as 56.5%, and for VuMan 3 as 5.6%

3.2 Cost

Navigator 1 's cost represents the cost of the off-the-shelf boards, plus the purchase price of components in quantities of one, plus the total cost of tooling and fabrication for the custom boards divided among the three units produced. The off-the-shelf boards include the 80386X processor motherboard, the Private Eye interface, VGA, A/D, Global Position Sensing (GPS), modem, disk, and mouse controller. The custom boards in Navigator include the GPS interface, on-set of speech detection, and power regulation.

VuMan 3\s cost includes the purchase price of components in quantities of one, plus the total cost

Board	Features Available	Features Utilized	Power Requirement
Ampro LittleBoard 386SX	• **Intel 386SX Processor** • System Management **Mode (SMM)~** • math coprocessor • **IDE HD interface** •upto 16MB DRAM • **serial ports (2)** • **parallel port** •**PC 104 bus** • watchdog timer • **keyboard connector** • **SCSI interface** • **floppy drive controller**	• **Intel 386SX Processor** • **System Management Mode (SMM)** • **math coprocessor** • **IDE HD interface** • **16MB DRAM** •**serial port(1)** • **parallel port** •**PC 104 bus**	+5V@ 1.0A
Pro AudioSpcctrum 16	• **audio record** • audio playback • stereo mixer • CD ROM interface • **SoundBlaster emuiadon** • **microphone**	• **audio record** • **microphone**	**(not specified)**
Private Eye	• **+I2V/+5V supply** • **CGA mode** • **CGA shadow mode** • **non-CGA mode**	• **+5V supply** • **non-CGA mode**	**+12V@0.24A,or +5V @ (current not specified)**

Table 1 - Navigator off-the-shelf board characteristics

Board	Features Available	Features Utilized	Power Requirement
Main Processor Board	• **Intel 386EX Processor** • System Management **Mode (SMM)'** •**1.25MB SRAM** • **DMA channels (2)** • **serial ports (2)** • parallel port • **PIC** microcontroller • real-time clock • **serial number chip**	• **Intel 386EX Processor** • **System Management Mode (SMM)** •**1.25MB SRAM** •**DMA channel (1)** • **serial ports (2)** • **parallel port** • **PIC** microcontroller • **real-time clock** • **serial number chip**	+3.3V@1.0A
PCMCIA Controller Board	• 82365SL PCIC chip • four buffers	• 82365SL PCIC chip • **four buffers**	+5V@ (current not specified)
Docking Station Board	• 8-bit D/A convener • 8-bit A/D convener • **PIC** microcontroller • watchdog timer • power-saving sleep mode	• 8-bit D/A convener • 8-bit A/D convener • **PIC** microcontroller • watchdog timer • power-saving sleep mode	+5V@ (current not specified)

Table 2 - Vuman 3 custom designed board characteristics

of tooling for the three different printed circuit boards and their fabrication divided among twenty units produced, plus the total cost of tooling and fabrication for housing divided among twenty units produced. A detailed breakdown of the costs, including components and services, as well as the list of suppliers for Navigator 1 and VuMan 3 can be found in [12].

3.3 Resource Utilization

An Integral Peripheral's IDE hard disk (75 MB) is used as secondary storage for Navigator 1. The application is a CMU Campus Tour, with speech input. The total disk space used by the initial Navigator 1 system was 62.5 MB. Discussions with the operating system group revealed that this was considered to be a minimal configuration. In an attempt to make a Flash Memory Card a feasible option for the Navigator 1's secondary storage, disk usage was first analyzed, using the UNIX tool *du,* and then systematically reduced. The initial distribution of disk space is shown by category in Table 3 [13]. It is clear that the prime consumers of disk space are swap space, system utilities, X Windows, the Campus Tour Application, and miscellaneous data. By condensing these areas in particular, a total of 45.5 MB of disk requirements were eliminated, for a total saving of 73%. The final distribution of disk usage is shown in Table 4. Much of the savings in disk space was accomplished by eliminating unneeded data files that had accumulated over time and by shrinking the unnecessarily large swap space However, the largest fraction of space was retrieved

Category	Space (MB)
Kernel	Z2
UNIX Server	2.9
Swap Space	10.0
System Binaries	3.0
System Utilities	10.6
X Windows	10.1
Campus Tour Application	9.6
Other	14.1
Total	**62.5**

Table 3: Initial Distribution of Disk Space in Navigator 1

Category	Space (MB)
Kernel	0.6
UNIX Server	1.2
Swap Space	2.0
System Binaries	1.0
System Utilities	1.2
X Windows	5.3
Campus Tour Application	5.5
Other	0.2
Total	**17.0**

Table 4: Final Distribution of Disk Space in Navigator 1

Category	Space (kB)
Hypertext Viewer	**22.5**
String Table	**0.4**
Document System Data	**314.0**
Total	**336.9**

Table 5: Distribution of Flash Memory Card Space in VuMan 3

by evaluating what tasks are likely to be performed on a wearable computer and eliminating space consumed by files serving other functions. For example, compilation can be done on a desktop machine and the binary then downloaded to the wearable unit; thus all files having to do with compilation were eliminated. The end result was a configuration that allowed the system to run on a Flash Memory Card with limited space.

The equivalent functionality Campus Tour application on Vuman 3 is an hypertext based application, where both system and application software code consume less then 0.35Mb of Flash Memory Card, distributed as shown in Table 5. The comparison between the amount of disk space used in Navigator 1 in relation to the amount of flash memory card space used in VuMan 3 clearly indicates that a much smaller amount of secondary storage space is needed for a custom designed computer.

3.4 Personpower

The personpower represents the amount of personnel effort required to complete all phases of the design methodology [3]. Records were kept throughout the Navigator I and VuMan 3 projects to evaluate the design methodology. Table 6 and 7 summarize the design effort among phases in the design and between disciplines. Since VuMan 3 represented an evolution of VuMan MA, the technology assessment phase was shorter then for Navigator I. Due to the custom nature of VuMan 3 the design phase in VuMan 3 required relatively more resources. The relative effort of **the** electronics group decreased as use of off-the-shelf boards and functionality increased in **the** Navigator 1 case as shown in Table 7. The VuMan 3 main housing unit with the input dial is almost the same as for VuMan MA, explaining the relatively smaller amount of personal effort put into the mechanical design.

Artifact	Technology Assessment (Phase I, II, III)	Design (Phase IV)	Implementation and Integration (Phase V, VI)	Total Effort (Person Months)
Navigator 1	28%	38%	34%	28
VuMan 3	19%	48%	33%	23

Table 6: Distribution of Design Effort for Navigator 1 and VuMan 3

Artifact	Electronics	Mechanical	Software and HCI	Total Number of Designers
Navigator I	34%	17%	49%	21
VuMan 3	49%	16%	35%	16

Table 7: Distribution of Person effort per discipline

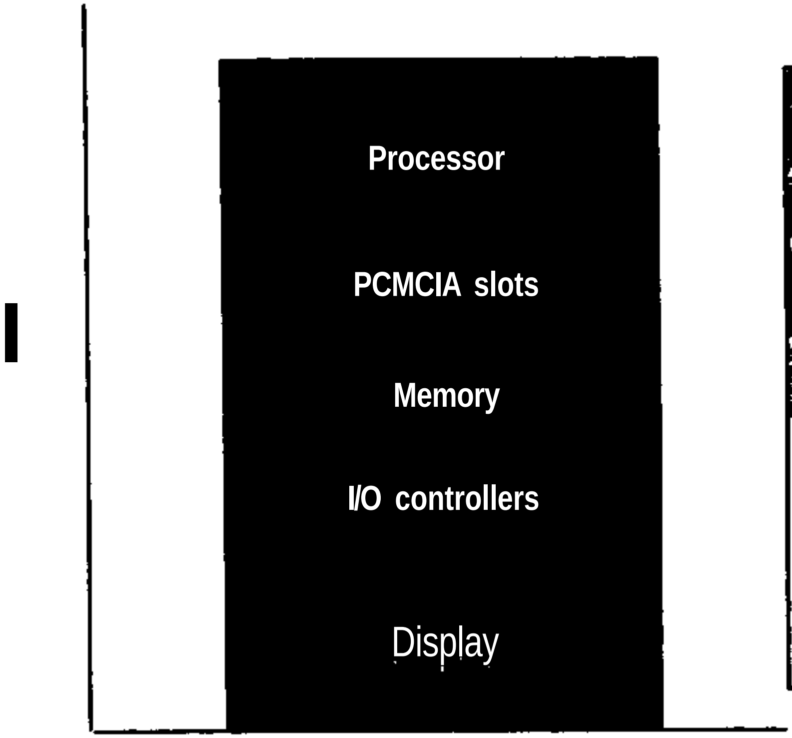
3.5 Power management

Power management can be performed at several levels, from the transistor level in hardware up to the application level in software. A fully custom design can build in features at each level, resulting in a wide range of options for power management. A semi-custom design, using both off-the-shelf and custom components, has fewer power management options available. Because the Navigator 1 was a semi-custom design, we evaluated its power consumption to identify areas for power reduction. Based upon the results of the evaluation, modifications were made to reduce power in the CPU board, the power supply, the hard disk drive, and the A/D board. The battery life and power for several combinations of these modifications were measured. With all the modifications in place. Navigator's battery life was increased from 2.6 hours to 7.5 hours, a factor of 2.9 improvement [9], and power consumption reduced from 15 watts to 7 watts. Figure 3 illustrates the VuMan 3 power consumption, and Figure 4 shows impact of power management on Navigator 1.

The 386EX processor and other components on the VuMan 3's processor board are using the 3.3 V power supply, what provides considerable power savings over 5 V components. A programmable PIC 16C71 microcontroller is used for power management and testing. The PIC microcontroller tests the battery voltage to check if the batteries are running on low voltage, and then turns on colored lights (LEDs). The PIC enables the processor when the power switch is turned on and disables the processor when the switch is turned off. When powered up, the PIC initializes it's internal registers, and then enables the INT interrupt, and goes into sleep mode which uses very little power. Power management software solution can be implemented in a flexible manner. Table 9 compares the power management features for Navigator 1 and WiMan 3. VuMan 3 consumes 1.5 watts, a factor of five less than Navigator 1.

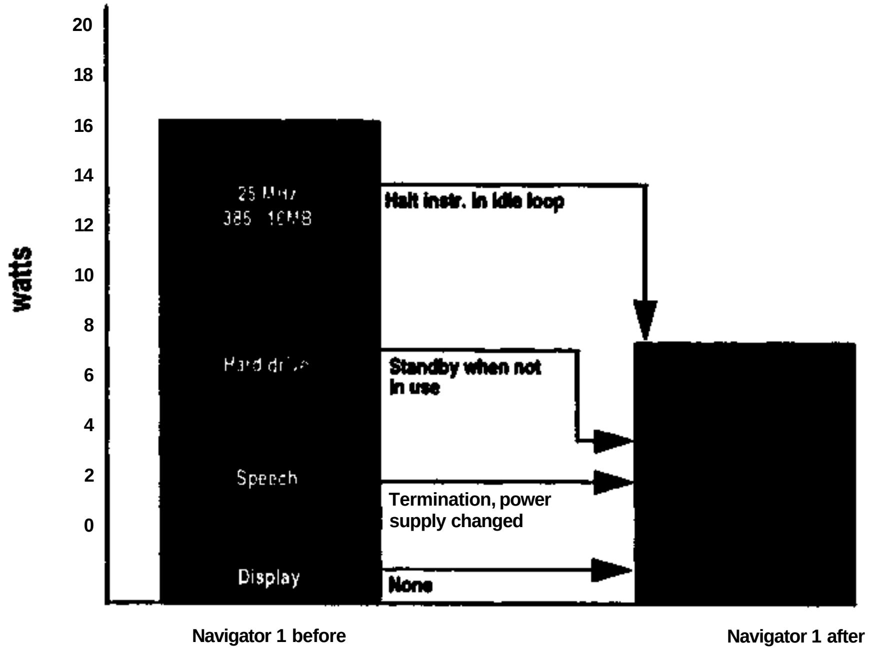
3.6 Software Portability

In porting the software from VuMan MA to VuMan 3,30% of time was spent on a problem related to different memory addressing schemes, which affected the 386EX low-level initialization, or bootstrap code. VuMan 3 contained over twice as much RAM (volatile memory) than our previous generation of VuMan, (M28kB, as versus 512kB). Because of the inherent memory addressing scheme of the 386EX processor, we have to initialize the processor and execute code in the Protected Mode (as it is called by Intel), which would allow us to access memory above the 1MB boundary. As the previous generations of VuMan contained less than 1MB of memory, this problem did not exist. Thus all the low-level/support code for both the bootstrap code, as well as the VuMan hypertext viewer was written for execution in Real Mode (easier to write, but does not access above 1MB of memory). Therefore, a significant portion of the existing code had to be rewritten to accommodate the increase in memory capacity. In a general purpose operating system environment, the compilers for protected mode of operation would alleviate this problem to a great extent. Several other implemented tasks depended on the ability to boot up 386EX, so that they could be tested, such as: a new interface to the Private Eye display using one DMA Channel for high-speed data transfer, Real-Time clock, and Silicon Serial Number Chip. Software portability for Navigator 1 and VuMan 3 is evaluated in Table 9.

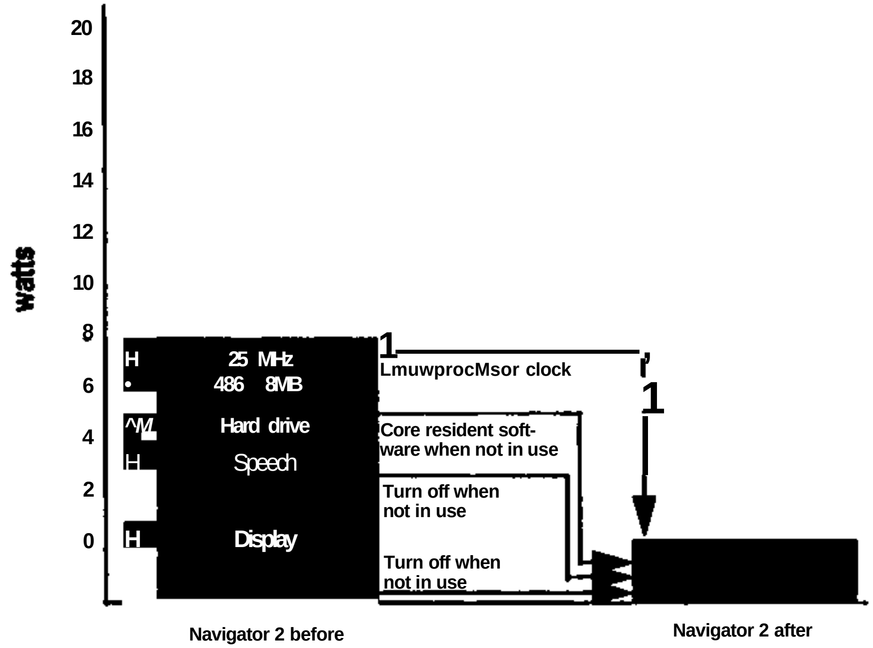


Vu Man 3 power consumption

Power Consumption in a Dedicated Wearable Computers



Navigator 1 power consumption



Navigator 2 power consumption

Impact of Power Management on Wearable Computers

Attribute \ Wearable Computer	Navigator 1	VuMan 3
Overhead Factor (%)	56.5	5.6
Cost ($)	4840	3550
Person power (months)	28	23

Table 8: Attribute comparison

Attribute \ Wearable Computer	Navigator 1	VuMan 3
Software Portability	95%	30%
Power (W)	7.5	1.5

Table 9: Attribute comparison

3.7 Storage requirements

Storage requirements characterize the amount of secondary storage space needed for system and application software, and data. The space needed on the VuMan 3's PCMCIA Flash EPROM Card was 0.35 MB, while the total disk space used by the initial Navigator I system was 62.5 MB, what is almost fifty times more than in the VuMan 3 case.

4 Conclusions

In this paper, we have studied rapid prototyping of Wearable Computers, focusing on custom versus off-the-shelf designs. These computers have a short design cycle, small batch sizes, and close interaction with the users. Based on representative examples from the six generations of the CMU Wearable Computers, we have evaluated both of these design styles. Six attributes characterizing these design styles have been defined: overhead factor, relative cost, storage resources, personpower, software portability, and power consumption. The off-the-shelf approach had ten times the overhead, 30% more cost, fifty times the storage resources, 20% more effort, five times more power, and 307c less effort to port software than embedded approach. Kiviat graph on Figure 5 compares these six attributes characterizing custom versus off-the-shelf design. Our results should provide a guide to future designers engaging in the rapid prototyping of real systems.

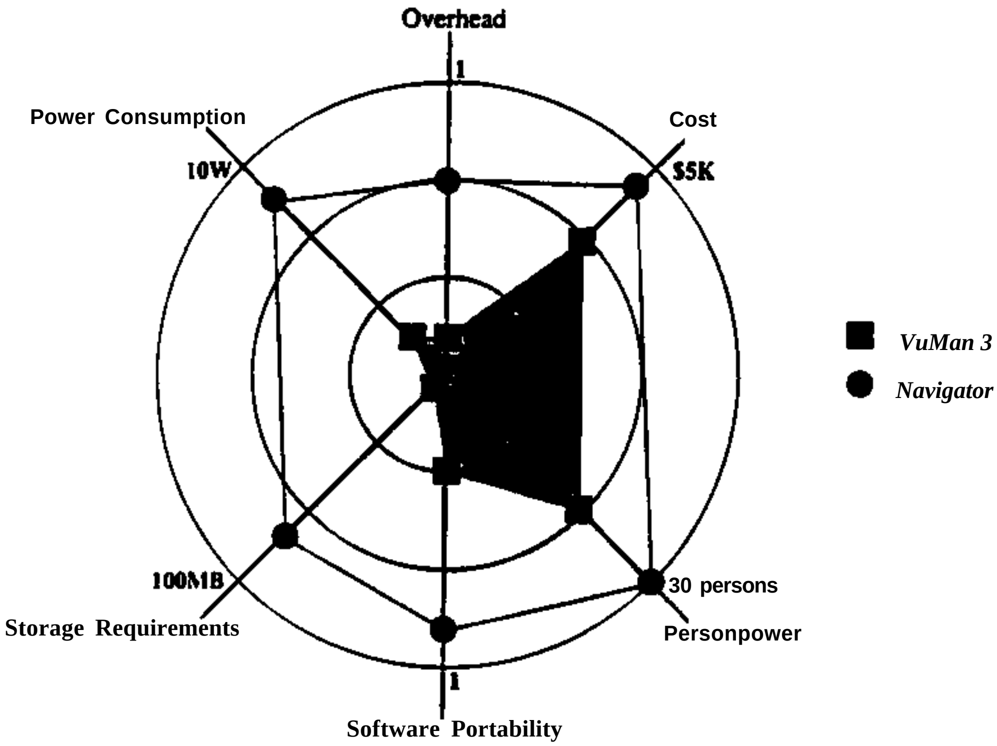


Figure 5: Kiviat Graph with six attributes characterizing custom versus off-the-shelf design

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