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**The Design and Implementation
of the VuMan Wearable Computer**

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Abstract*

This paper describes the design and implementation of a novel embedded computer system with a visual interface - VuMan 2. VuMan 2 is the most recent wearable computer artifact designed and implemented at Carnegie Mellon University. VuMan 2's capabilities and an evaluation of its design process are presented. Our learning experience and experimental results should contribute to a better understanding of new emerging information technology concepts as well as the process of embedded systems design.

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1 Introduction

Wearable computers are at the leading edge of a new generation of computer systems. In essence, the wearable computer moves with the user, it accompanies the user and tracks his/her motions in both time and space, providing real time information which extends the user's knowledge and perception of the work environment. The convergence of a variety of technologies makes possible this paradigm shift in information processing. Continued advances in semiconductor technology makes possible high performance microprocessors requiring less power and space. Decades of research in computer science have provided the technology for hands-off computing using speech and gesture for input. Miniature heads-up displays weighing less than a few ounces have been recently introduced. Combined with mobile communication technology, it is possible for users to access information anywhere. It is indeed possible to sense a user's position so that the relevant information can be superimposed upon the user's workspace.

Carnegie Mellon University has designed and manufactured two generations of wearable computers: VuMan 1 [2,3] and VuMan 2. Currently we are implementing the third generation wearable computer called Navigator, which will provide hands-off operation through a speaker independent speech recognition system. It also provides greater user interaction with the physical environment by supporting position sensing, allowing the system to provide the user with real time information directly relevant to his/her current interaction with the workspace. Support for augmented perception provides the user with a means of viewing details of the work environment which are otherwise invisible or available only through extrapolation [11]. We are creating a new generation of wearable computers approximately every eight months. Each generation provides a learning experience and experimental testbed enabling advancement towards the next generation. In addition to the artifact, we also learn through observing the design process.

The VuMan 2 is an embedded system consisting of custom built hardware, software and application programs. The hardware development occurred in parallel with the software development. The implementation and use of the target system simulator as well as CMU's Engineering Design Research Center's (EDRC) concurrent engineering design environment made this approach viable [7].

Section 2 defines goals and provides background information on the wearable computer project. Section 3 focuses on the design process and implementation of the hardware, software and housing for the VuMan 2 wearable computer. This section contains descriptions of the major project milestones and the problems encountered during the project realization. The design time and effort distribution is compared to the VuMan 1 project. Section 4 contains concluding remarks and proposals for future research.

2 Background

2.1 Project Goals

The main goal of the VuMan 2 project was to rapidly prototype a reduced size and complexity wearable computer with enhanced capabilities than its predecessor VuMan 1:

- **Rapidly prototype:**
 - **Reduced size: one half pound, belt-mounted**
 - **Reduced complexity: new printed circuit board with fewer chips made possible by a Flash Memory Card and an Electrically Programmable Logic Device (EPLD).**
 - **Stereo-lithography Apparatus (SLA) manufactured conformable housing**
- **Enhanced functionality: menu driven software for displaying a variety of information including maps, images, and text allowing location of persons and buildings on campus using only limited information**

A secondary goal was to test individual tools developed at EDRC in an actual design and to accelerate the integration of tools from different projects into a single design environment.

2.2 The predecessor - VuMan 1

Over a 12-week period during the summer of 1991, in conjunction with a Carnegie-Bosch Institute continuing education course, we conceived, designed and manufactured our first generation wearable computer called VuMan 1. Initially, VuMan 1 was specified to be a small portable computer weighing less than one kilogram, Figure 1, for displaying construction blueprints, Figure 2. VuMan 1 allows the user to maneuver through a set of blueprints using a simple, multi-button interface which required little user training. VuMan 1 provides scrolling up/down and left/right, and zooming out/in. A head-mounted display, the Private Eye [1], that was originally designed for use with desk-top personal computers was selected for the VuMan 1 project. The Private Eye provides a screen 3/4 x 3/4 inch mounted on a head set. The screen weighs approximately two ounces and is positioned within a few inches of the user's non-dominant eye. In this position, the Private Eye assumes many of the properties of bifocal glasses. The user can either look at the outside world or at the screen with minimum eye refocusing. The net result is the illusion of a standard size computer monitor floating approximately five feet in front of the user.

VuMan 1 was manufactured from conventional printed-circuit board technology. The final version of VuMan 1 has the following characteristics:

- **Electronics:**
 - **Intel 80188,8 MHz processor chip**
 - **up to 8 64 KBx8 EPROM chips holding bitmap images for on-screen display**
 - **8 KBx8 RAM chip**

- AT Bus Backplane
- Private Eye CGA Adaptor Card
- 12 chips of random logic
- on/off power switch
- reset push-button
- 2.5 x 5.5 x 12 inch vacuum molded enclosure
- Powered by 8 x 1.5 V batteries or a 12 V DC source
- Weight: 3.3 lbs
- Power: 3.8 W
- Three application push-buttons

VuMan 1 was designed for ease of use through the manipulation of on-screen icons. Three switches are grouped at the bottom of the hand rest. The center switch selects one of the function icons at the bottom of the screen. Each time the center switch is depressed, the next icon in sequence is selected. The two outer switches at the base of the hand rest select the left or right function highlighted in the selected icon. For example, the scroll up, scroll down icon will scroll the screen image by one-eighth of the screen size each time the outer switches are depressed. VuMan 1 is equipped with one adjustable shoulder strap for wearing on a shoulder or across the chest. Operation is with a single hand and does not require the user to see the input push-buttons. The system is easy to use for either left-handed or right-handed people.

The following problems in the VuMan 1 implementation were noted:

- While the cursor keys are intuitive they do not really correspond with how people operate the software. Up/Down is rarely used in sequence. In general people tend to want to go to a place and move to it using either Up/Left, Up/Right, Down/Left, or Down/Right.
- Zoom is slow, and generally seems to be used relatively rarely compared to the scroll keys.
- The bottom row of icons reduces the display space for blueprints
- In general it takes too many key strokes to get from one place to another.
- It is not completely clear to novice users what each function does.

Section 3 describes how these limitations were addressed while meeting the project goals for VuMan 2.



Figure 1 Several photographs of VuMan 1, showing the head-mounted display (top), and exterior (center) and interior (bottom) views of the processor and battery pack

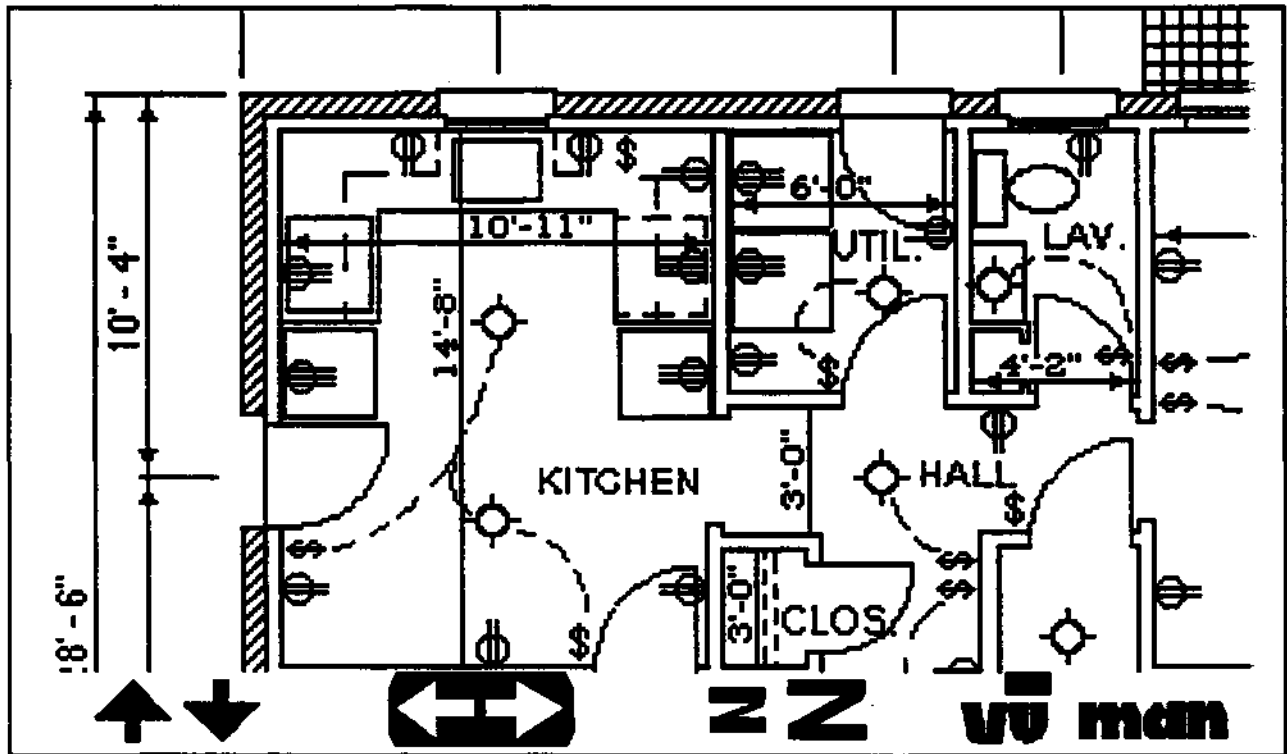


Figure 2 View of user screen in VuMan 1, showing icon controls for scrolling up/down or left/right (currently selected in inverse video), and zooming out/in.

3 Design, Implementation, and Manufacture

3.1 Technology Assessment

There were three phases in the VuMan 2 project:

- *Technology Assessment*, which consisted of a Technology Survey and a Feasibility Study (including wirewrap prototyping)
- *Design*
- *Manufacture*

The Technology Assessment phase of the VuMan 2 project started during the late summer of 1992 by studying ways to reduce the complexity of VuMan 1. VuMan 1 was composed of three boards: the Private Eye CG A adaptor card, an AT bus backplane, and the embedded computer. Experience with the VuMan 1 design suggested that it was possible to interface the embedded computer directly to the Private Eye display, thus removing the CGA adaptor card and the AT bus backplane. A newly available technology, Flash EPROM Memory Cards, made it possible to replace the seven bitmap EPROMs. The Flash Card was easier to remove and program than the EPROM chips. Using the Flash Memory Card also enabled the user to have access to more than twice as many bitmaps as in VuMan 1. Another relatively new technology, Field Programmable Gate Array (FPGA) chips could replace the discrete MSI "glue logic" chips with a single chip. A preliminary breadboard was used to verify the feasibility of directly driving the Private Eye display and the use of Hash Memory Card for storage of screen displays.

There were several problems encountered while making these initial modifications, that were solved in the first part of the design phase (see Section 3.3). A wirewrap prototype of the design verified the modifications. Other technologies considered during the assessment phase included mechanical structure, thermal properties, software development, and human interface. The assessment phase for each of these technologies will be described in the following sections.

3.2 The Artifact: VuMan 2

In order to place the design process in context, it is instructive to first understand the final design of VuMan 2. The final version of VuMan 2, shown in Figure 3, has the following characteristics:

- **Electronics:**
 - Intel 80C188EB, 13 MHz processor chip
 - 1 MB Flash EPROM Memory Card for programs and bitmap screen images
 - 512 KBx8PSRAM chip
 - 128 KBx8 EPROM chip for programs
 - Altera EPM7096JC EPLD chip with 96 macrocells, 1,800 gates actually, used for random logic

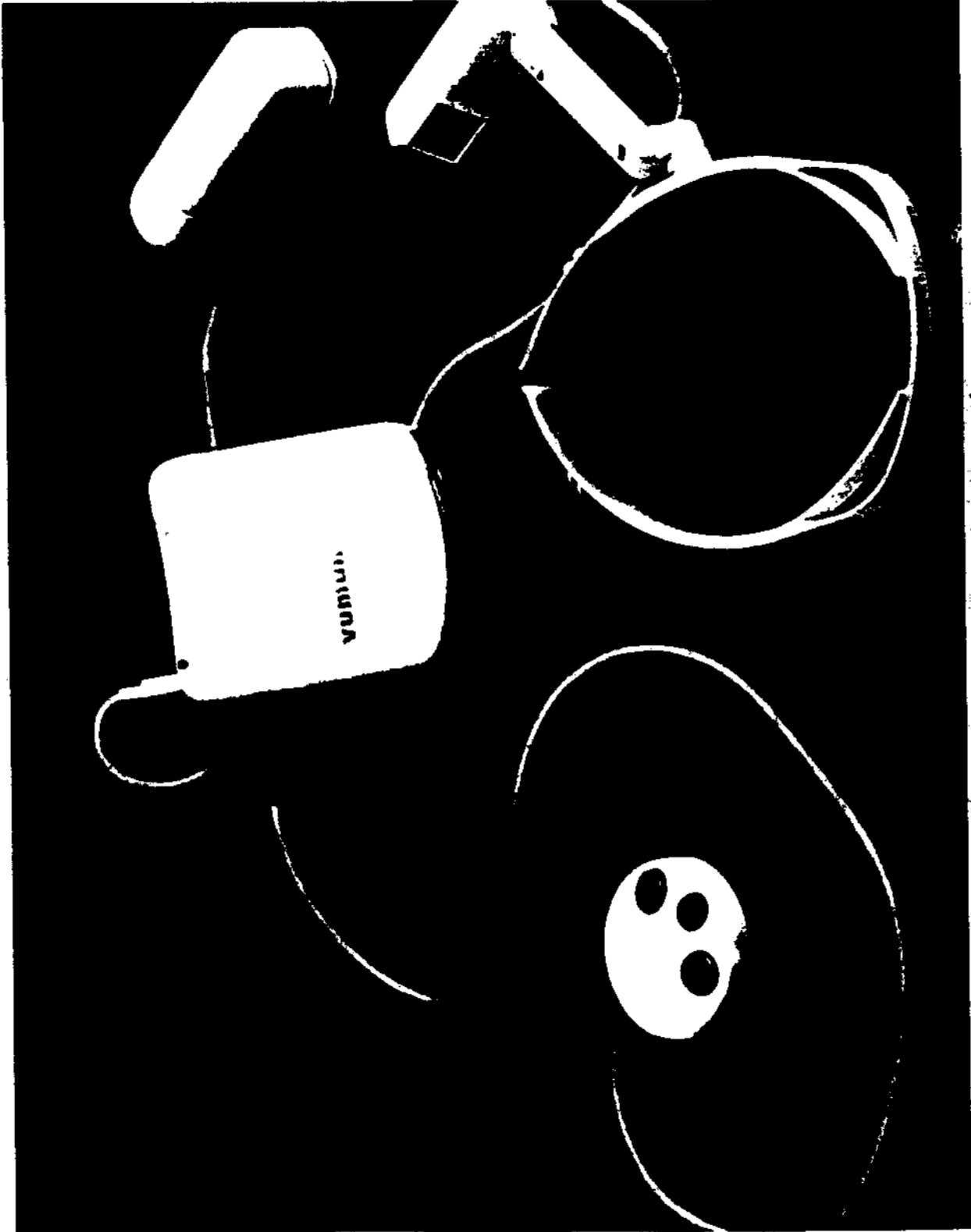


Figure 3 Photo of VuMan 2 including mouse, main housing, display, and battery (left to right)

- On/off power switch
- Reset push-button
- Eject button to replace Rash Memory Card
- Reflection Technology's Private Eye Display, 720x280 resolution
- 1.5 x 4 x 4.4 inch housing fabricated with the Stereo-Lithography Apparatus (SLA)
- Battery housing for 12V Varta's rechargeable NiCd batteries
- Mouse with three application push-buttons

Notice that VuMan 2 required only five electronic chips compared to 25 chips for VuMan 1.

3.3 Design and Manufacturing

3.3.1 Electronic Design Evolution

The direct interface to the Private Eye display, removed the overhead of the CGA adaptor card and AT bus backplane. The preliminary breadboard demonstrated that the reduced interface was feasible. The breadboard interface circuitry included a 22V10 PAL, 8-pin Mini Din female connector, some resistors and two D flip-flops. This implementation was very similar to the IBM PC parallel port. In VuMan 1, software communicates with the Private Eye by writing data to a RAM and display commands to 10 registers on the GGA card. Writing to the Private Eye with the direct interface involved writing to an 10 port As documented by Reflection Technology, this interface involved significant changes in software. One major change was that the image must be rotated 90 degrees before being written to the Private Eye. A rotation filter program was written to solve this problem. Display software was modified to write commands containing address information and image data bytes to the 10 port

The newly available *Flash EPROM Memory Card* technology replaced the seven EPROM chips (each 64 KB) from the VuMan 1 artifact. The Flash EPROMs are 68-pin Epson PCMCIA memory cards with a 1MB capacity each. The size of a credit card, the Flash EPROM is inserted into a card holder equipped with an ejecting mechanism. A Flash card programmer from Adtron Corp, which plugs into the parallel port of an IBM PC, provides quick updating capability. The Flash cards were easy to add to the VuMan 1 design, as their electrical specification was similar to the 27C512 EPROMs used in VuMan 1, including address lines, data lines, Output Enable, Chip Select, etc. The wirewrap breadboard implemented during the Technology Assessment phase of the VuMan 2 used only 64 KB of bitmap (approximately four screens of data). In the final design, the entire 1 MB of Flash memory provided over 60 screens of information.

In order to minimize the number of chips on the VuMan 2 board an *Altera EPM7096 EPLD chip* [5], which is a high-density, high-performance 96-macrocell device, was selected during the early design phase to logically "glue" together the processor chip, memory chips, and Flash Memory Card. This CMOS EPLD provides 1,800 usable gates with propagation delays of 15 nsec. It easily provides the equivalent of multiple programmable logic devices ranging from PALs, to GALs, to 22V10s, to FPGAs. For building complex logic functions, each macrocell can be supplemented

with both shared expanders and high-speed parallel logic expanders to allow up to 32 product terms per macrocell. The EPLD has 60 I/O pins that can be individually configured for input, output, or bidirectional operation. All 60 pins were used for VuMan 2. The EPLD also has 4 dedicated input pins (Clock, Clear, and two Output Enables) that can be programmed as general-purpose inputs or high-speed, global control signals for each macrocell and I/O pin. The EPLD provided the following functions: address latches for the RAM, EPROM and Flash Card, Private Eye interface, Flash Card interface, button interface and switch debouncers. The EPLD also implemented paging memory so that the entire 1MB of the Flash Memory could be easily accessed. The EPM7096 EPLD offers a power-saver mode that supports low-power operation across user-defined signal paths or the entire device. This feature allows total power dissipation to be reduced by 50% or more, since only a small fraction of all gates operate at maximum frequency in most logic applications. An Altera Development System, connected to an IBM PC, was used to program the EPLD. By replacing the Private Eye interface, using the Flash Memory Card, and using the EPLD we were able to eliminate 12 chips from the VuMan 1 design. Figure 4 shows the block diagram of the VuMan 2 implementation including the EPLD.

The schematics for a wire list for the printed circuit board was produced by *DP (Draw Program)*. The wirelist was input to *Tango PCB Plus*, a commercial program tool for board layout and placement. The routing was done by *MaxRoute*, Version 4. The CAD/CAM files were then sent to a printed circuit board manufacturer. The VuMan 2 board is composed of four layers including power, ground, and two signal layers. The board is 1/16th of an inch thick. Eight VuMan 2 PCBs were manufactured in two weeks time.

3.3.2 Mechanical Design and Fabrication

One portion of the Technology Assessment phase evaluated the feasibility of using mouse buttons as input, instead of having the push-buttons on the artifact's enclosure, as in VuMan 1. This study concluded that a separate mouse with three input buttons was a desirable addition. The study also concluded that the battery compartment should be removed from the main housing enclosure and made a separate module. Both of these decisions further contributed to the reduction of the VuMan 2. Figure 5 shows a comparison of VuMan 1 and VuMan 2 sizes.

The assembly process for VuMan 1 was slow, composed of over a dozen screws and nine discrete wires which were cut/stripped/soldered. Another goal of VuMan 2 was to decrease assembly/disassembly time. During the initial design phase mechanical engineers worked with electronic engineers and industrial designers to develop an assembly process based on snap fitting. Figure 6 illustrates how VuMan 2 uses snap-fits as the main assembly technique. The printed circuit board and the Flash Card holder are presoldered. The board and the Card holder are snap-fit into the back housing plate where they are placed on alignment pins. A heat spreader and conductive material (aluminum) are attached for heat dissipation. Both sides are pressed together, again held with snap-fits.

In order to allow concurrent hardware and housing development a full scale, non-functional printed circuit board, shown in Figure 7, was fabricated. The physical prototype board provided detailed geometric information for the CAD drawings and housing design so that a ProEngineer mechanical model [6] could be built and a thermal analysis performed. Designs for the main housing, battery pack, and mouse were entered into the CAD data base of ProEngineer. Details of the design, such

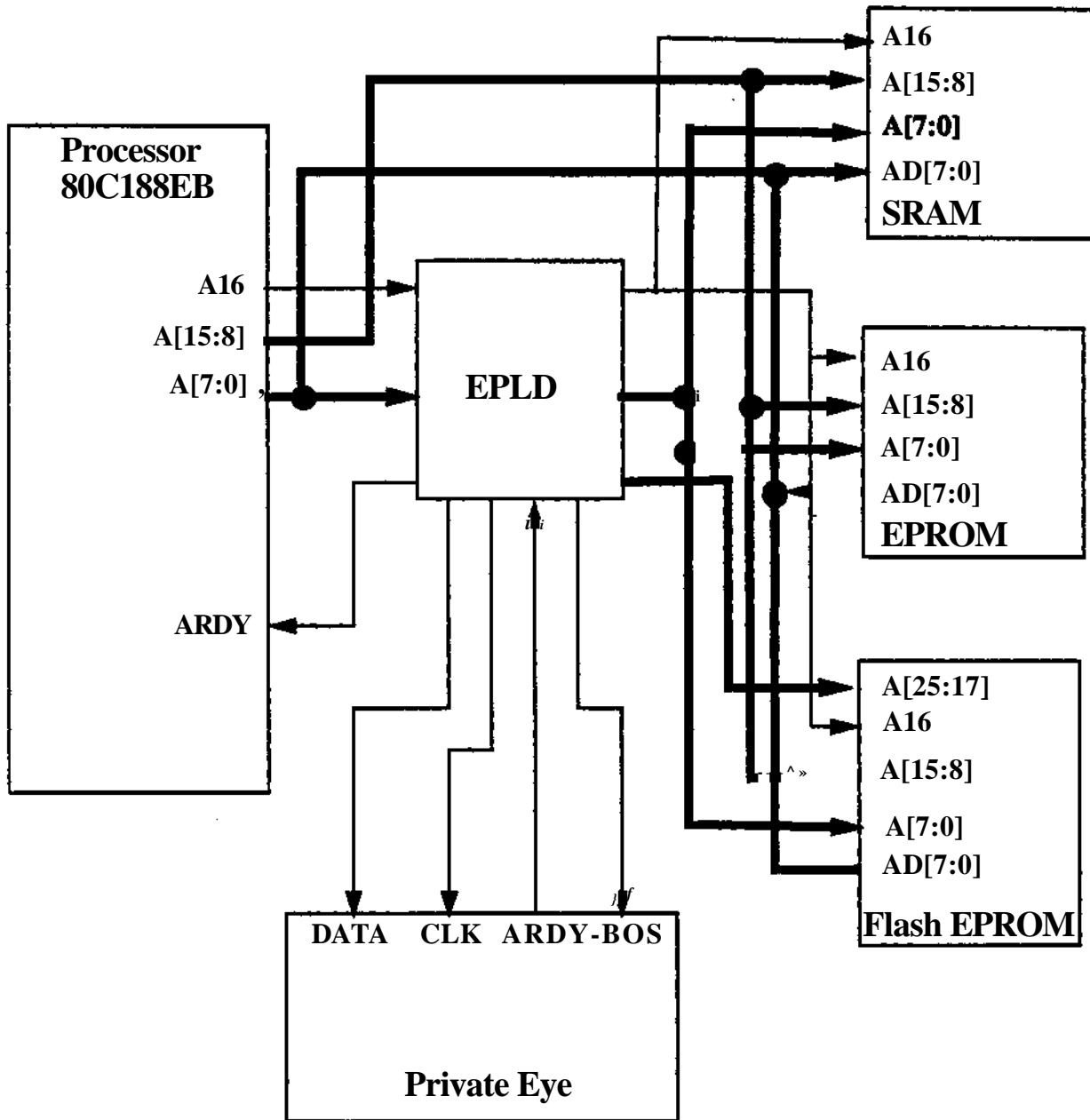


Figure 4 Logical block diagram of VuMan 2

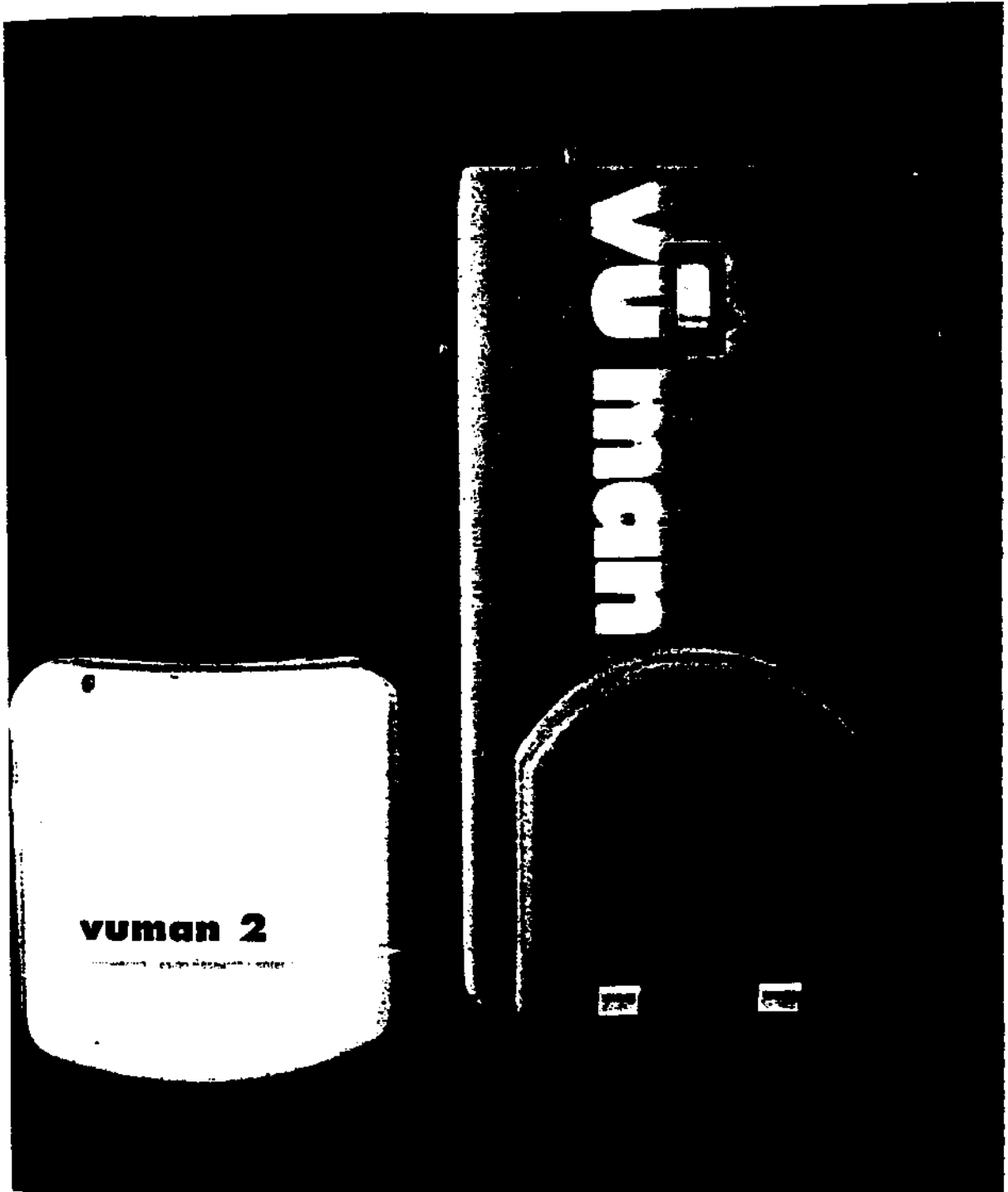
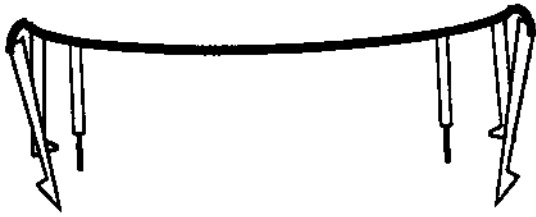
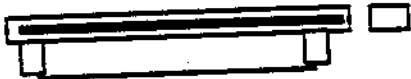


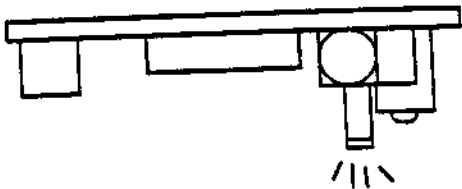
Figure 5 Comparison of VuMan 1 and VuMan 2



Back Housing



Flash EEPROM Holder



Main Board



Thermal Pad



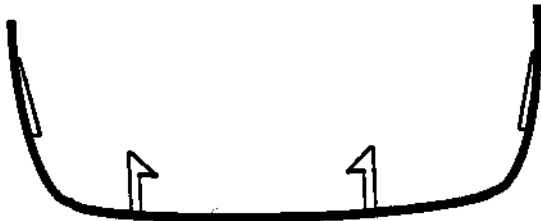
Conductive Material



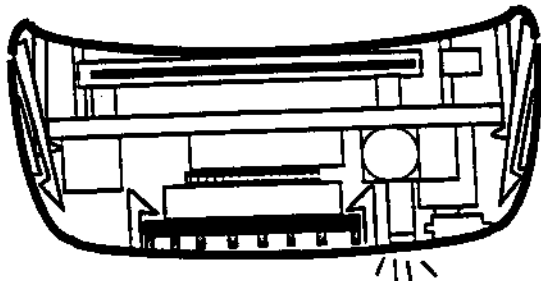
Heat Spreader



Button Cover



Front Housing



**Assembled
VuMan 2**

Figure 6 VuMan 2 Housing Model

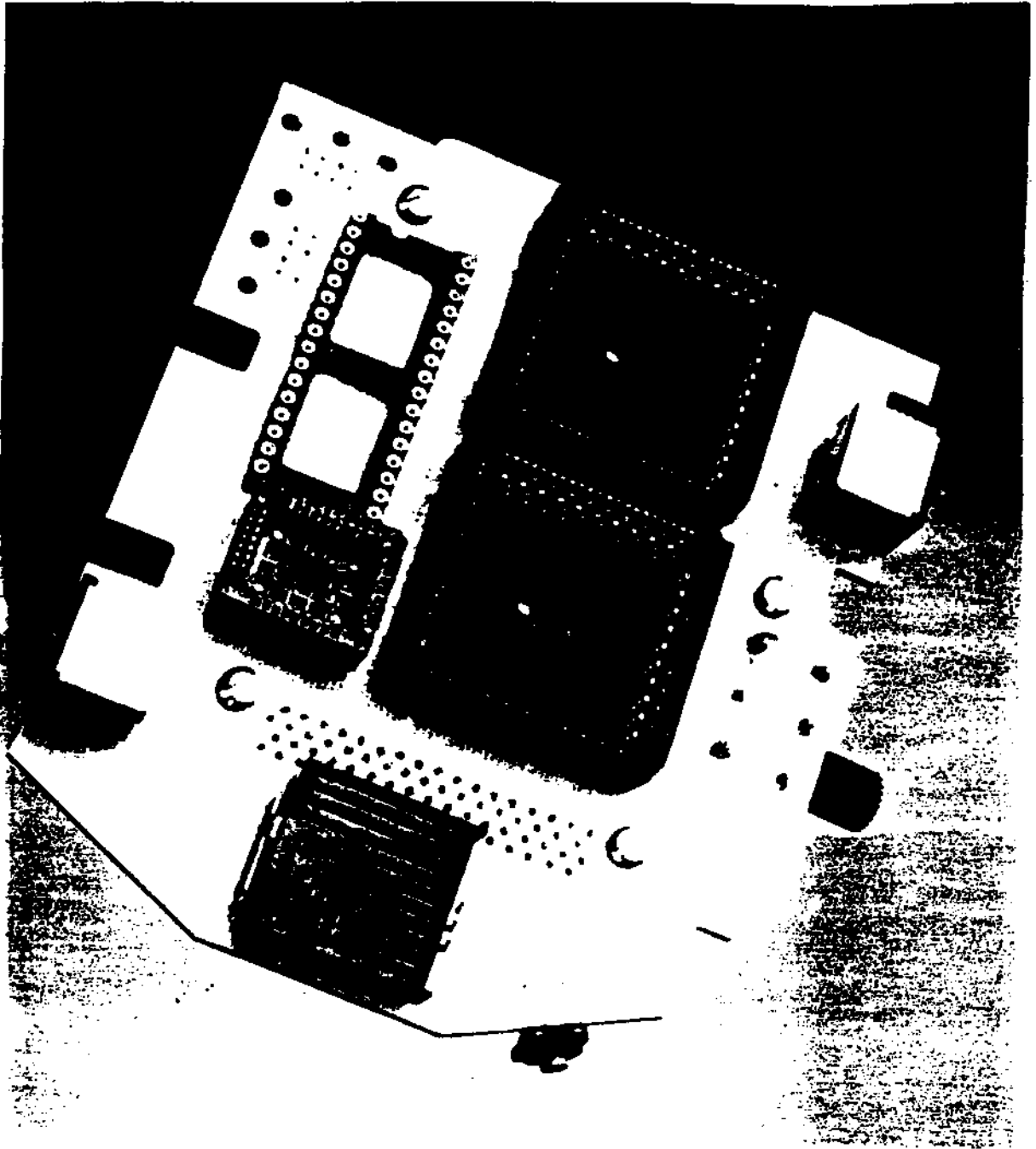


Figure 7 Prototype of the VuMan 2's PCB

as holes, slots, and snap-fits, were also entered into the CAD system. The support structures required for fabrication by the stereo-lithography apparatus (SLA) were added last. These files were then translated into the format necessary to drive the on-campus stereo-lithography apparatus. The SLA process was chosen primarily for its rapid prototyping capability. The SLA fabrication process starts by intersecting the three dimensional solid model with a set of parallel planes [9]. The result is a set of two dimensional areas representing layers of the final housing. A raster pattern is created to drive a laser which writes into a vat of liquid photosensitive plastic. The areas illuminated by the laser solidify creating one layer. The process is repeated until the final structure emerges. Support structures, required for features which overhang, are removed and the surface finished. The housing was made using SOMOS 2100, a strong plastic which can be sanded, painted and machined. Due to the brittleness of this material, it is important that the snap-fit be designed with enough stress tolerance to avoid breaking due to excess deflections or fatigue. The maximum thickness of the housing is 1.5 inch. The package wall thickness is 0.125 inch.

3.3.3 Application Software

The VuMan 2 software includes the following major functions:

- Screen display
- Screen scroll
- Low-level graphical support
- Simulator
- Campus/Building Map Translators
- Text Translator
- Font Generator
- User interface for Campus navigation
- On-board embedded monitor software

VuMan 1 software consisted of only the first three functions.

The VuMan 2 *Simulator*, written on a PC, was very helpful throughout the hardware/software co-design phase. It turned out that the Simulator very accurately described the VuMan 2 behavior. When the design and implementation of the Simulator started, the main problem was that the code which runs on VuMan 2 and the code which runs on the PC Simulator could not be the same, since the new hardware used in VuMan 2 did not use a CGA card which the PC Simulator used. The Private eye display operates differently without a CGA card, as it becomes a column based display instead of a row-based display.

The format change had a major impact on the implementation of the *Displayfunction*, in the way the Display function must walk through the bitmap and write the bytes to the screen. Also, the manner in which the bitmaps are stored in memory had been changed to enable the Display function to more easily retrieve bytes from the bitmaps. A collection of off-line *Translators* were used to generate bitmap files acceptable by the Flash Card programmer. The VuMan 2's display has an aspect ratio of 2:1 (pixels are twice as tall as they are wide).

During the early design phase for VuMan 2 it was realized that there was no way of monitoring the execution of code on the VuMan 2 hardware once the code had been programmed into the Flash Card. Occasionally problems arise that are specific to the VuMan 2 hardware and would not be found using the simulator on the development system. Therefore, it was decided to incorporate the ability to monitor code execution on the actual VuMan 2 hardware. The monitor enables a software developer to interface with VuMan 2 and display processor state as the code is executed. The functions provided by the monitor include: setting breakpoints, single-step execution, displaying register values, and displaying memory locations. The monitor involves executing code located in the VuMan 2 RAM and receiving monitor commands from a host PC connected to the processor via a serial port. The 80C188's INT instruction is used to set breakpoints. Single-stepping is provided using the Trace flag in the 80C188's status register, and data value displaying, including registers and memory, is supported by allowing the processor to send data it obtains back to the host, and providing simple display routines to display the data on the host's screen for the programmer.

3.3.4 Menu Driven User Interface (UI)

The goal of the VuMan 2 project was to build a personal campus navigation compute; supporting functions such as:

- Allow the user to locate a building on campus using only limited information about a person's name, the building's name, or general directions.
- Allow the user to find phone numbers, office locations, and other information about a person.
- Provide the user with information about special amenities such as dining areas, phone locations, handicapped equipped areas, computing facilities, etc.

In order to achieve these goals, the user interface was designed to:

- Be explained or demonstrated to a novice user in approximately one minute.
- Minimize the number of keystrokes necessary to get from one option to another.
- Not hinder the user as he/she becomes more familiar with the device, progressing from novice user to expert user.
- Be consistent between different screens, further supporting rapid familiarization.
- Provide constant reminders on the screen indicating what function each key performs.
- Provide cursor control to allow the user to move on screen to select different text areas.
- Provide optional help that specifically indicates to the user what the current function does.

The interface allows the user to move a cursor across the display and select items from either a map of campus or from a menu, as shown in Figure 8. The menu selections allow the user to change the map view, search databases along fields such as person or building name, request help, etc. VuMan 2 is capable of providing biographical information on people, buildings and departments, as well as displaying pictures of buildings from an image database.

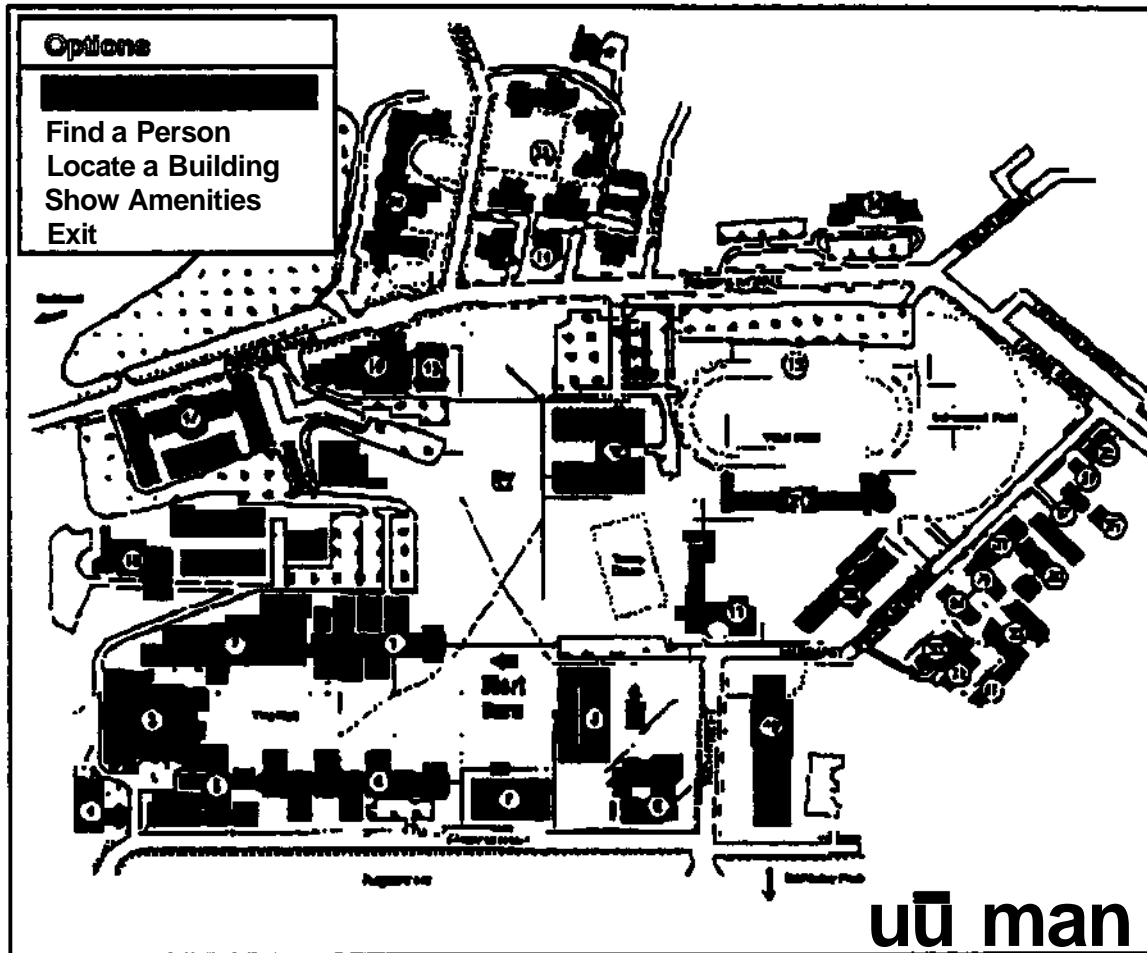


Figure 8 Example of screen in VuMan 2, featuring a pull-down menu.

3.3.5 Batteries and Power consumption

The power consumption is as follows:

- At 10 V, the maximum current was 156 mA (running through the demo) for 1.56 W. The minimum current is about 110 mA for 1.1 W.
- Note that the 5 V supply for VuMan 2 would have about twice the current, with allowances for efficiency. With an efficiency of 85% (a typical number, verified by our previous tests) the current would be about 1.7 times the input current, or 187 mA to 265 mA.

The 12 V Varta's rechargeable NiCd battery pack lasted over 3 hours on VuMan 2. The AA's battery pack lasted 2.5 hours.

3.3.6 Thermal analysis

From a thermal perspective, a computer system is an intricate composition of many different materials and geometries. Accurate prediction of operating temperatures requires the coupled solution of both solid and fluid domains. A concurrent thermal design methodology suitable for the rapid prototyping of electronic equipment [10] was developed in conjunction with the VuMan 1 project. This methodology assesses the effect of geometrical, material, and processing variation upon the heat transfer characteristics of electronic components and assemblies.

During the initial phases of design, details on geometry, material, and power dissipation are imprecise. Thus a simple thermal model provides an indication as to which method(s) of heat transport are required to cool the electronic system. Figure 9 indicates the plot used in the MiMan designs. Along the x-axis is plotted the surface heat flux and along the y-axis, the temperature

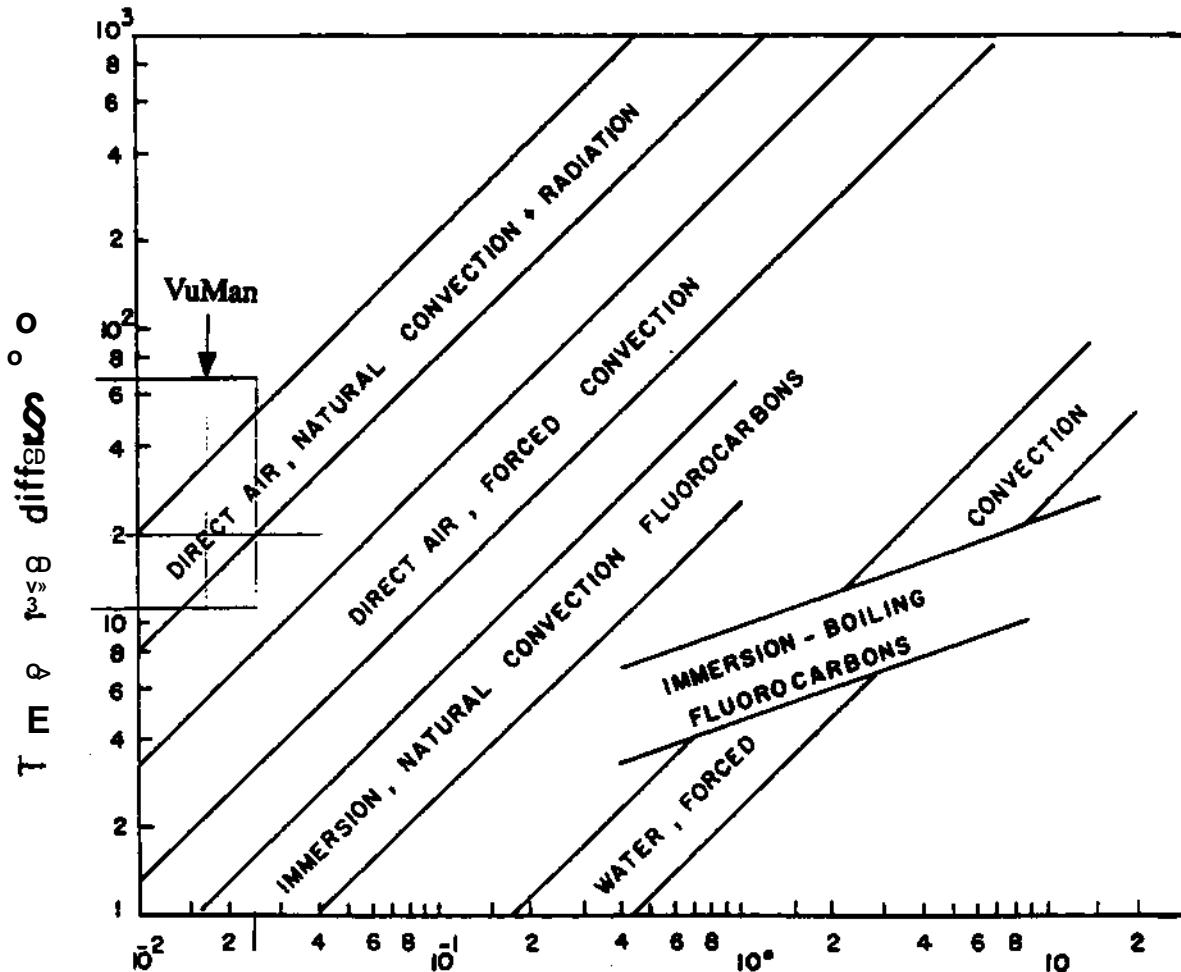


Figure 9 Surface heat flux (W/cm²) for VuMan 2

difference between the average system temperature and the ambient. The designer calculates the operating point of the system and then checks which mode of heat transport can be used. The information provides the thermal analyst with an indication as to the necessity of additional

equipment, such as a fan or fins. In the case of VuMan it was determined that natural convective cooling using ambient air was quite acceptable. As the electronic and structural designs evolve, a series of more accurate thermal models are used to analyze the design. Ultimately conductive/convective analysis on two-dimensional cross sections fine tune the predictions of the earlier models. Figure 10 shows the temperature and velocity fields for the cooling fluid (i.e. air) in VuMan 1. Note that there is a 70° centigrade temperature rise in VuMan 1 concentrated around the voltage regulator chips. The location of high temperature regions is particularly important for wearable computers. The detailed thermal analysis of VuMan 2 indicated no problem areas.

3.4 The Design Process: Personpower

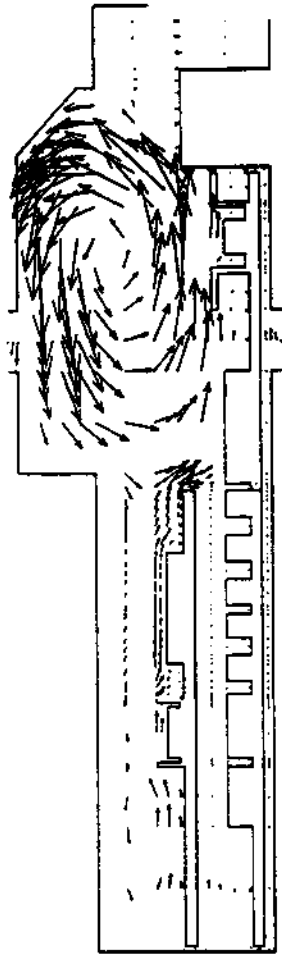
The complete design and manufacturing process for VuMan 2 took 138 person days in contrast to the 229 person days for VuMan 1. Figure 11 shows how the total personpower for these two projects was split between the three phases of the design process. Figure 11 clearly illustrates how the VuMan 2 project took advantage of the VuMan 1 design efforts. The Technology Assessment phase was significantly reduced from 33% for VuMan 1 to 17% for VuMan 2. Thus more effort could be spent to enhance the functionality and manufacturability of the VuMan 2 artifact.

Figure 12 describes how the total personpower was split between the three disciplines: hardware, software, and housing. Much more effort was placed on the user interface software development for VuMan 2, as is clearly reflected in Figure 12 (6% vs 31%).

Figure 13 and 14 show the various tasks and the personpower involved in the design and manufacture of VuMan 1 and 2 respectively. The vertical axis represents calendar time. Each bubble is a task. The width of the bubble is the maximum number of persons who worked on the same task. Bubbles next to each other represent concurrent tasks. The area of the bubbles does not directly correspond to the personpower, since there was not usually someone working full time on a single task from start to completion. The software for VuMan 1 was developed/debugged directly on the embedded system. In order to allow concurrent hardware and software development, a VuMan 2 emulator was created on a conventional PC. Over 90% of the software effort occurred in the PC environment. In addition, to allow concurrent hardware and housing development, a full scale non-functional printed circuit board (PCB), shown in Figure 7, was fabricated. The prototype board provided detailed geometric information for the housing designers so that a ProEngineer mechanical model could be built and a thermal analysis performed.

Figure 15 shows the main tasks of the design and manufacture process with respect to the appropriate design stage (or designer) and manufacturing stage. The vertical axis represents time. Each bubble represents a task. An arrow between two tasks represents both a precondition in time and a communication point between designers (or manufacturers). Software & UI I relates to the design and implementation efforts on the development computer platform (386 PC), while Software & UI II relates to the implementation efforts on the target computer - VuMan 2.

The lessons learned from the VuMan 1 design, such as the importance of continual communication within the project team and the importance of maintaining consistency with the original design concept in a multidisciplinary technical environment, helped us to minimize rework effort.



Velocity Field



Thermal Field

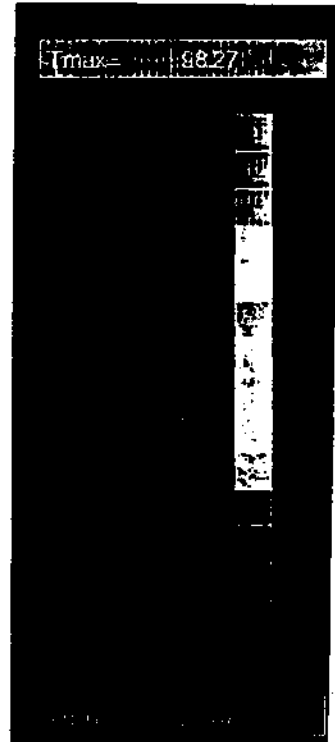


Figure 10 Temperature contour graph of a cross section of VuMan 1

Table 1 summarizes the attributes of the CMU wearable computers. The following improvements made in the VuMan 2 artifact in comparison to VuMan 1 can clearly be seen from this Table: reduced dimensions, number of chips, power consumption, and weight. The data for Navigator shows the dimensions for the largest housing module. There are also two others smaller housing modules: global position sensing (GPS) and wireless telecommunication.

Artifact	Delivery date	Number of units	Processor	RAM/ROM	Input	Display resolution	Dimensions (inches)	Chip count	Power (W)	Weight (lbs)
VuMan 1	Aug91	30	80188 8 MHz	8KB 512KB	3-button	720x280	2.5x5.5x12	24	3.8	3.3
VuMan 2	Dec 92	7	80C188 13 MHz	512KB 1MB	3-button	720x280	1.5x4x4.4	5	1.1	0.5
Navigator	Jun93	3	80386 25 MHz	16MB 85MB	speech	720X280	2.5x6.5x10	65	25	10

Table 1 Hardware characteristics of the CMU wearable computers

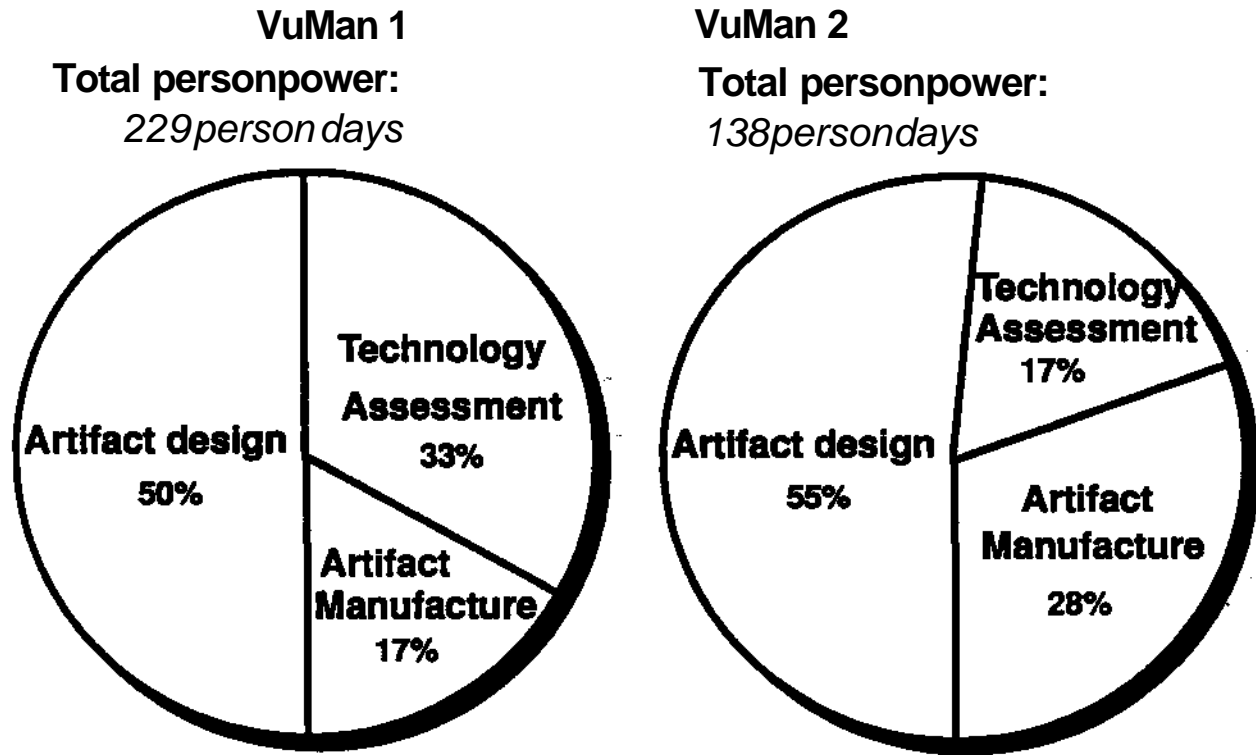


Figure 11 Personpower per task

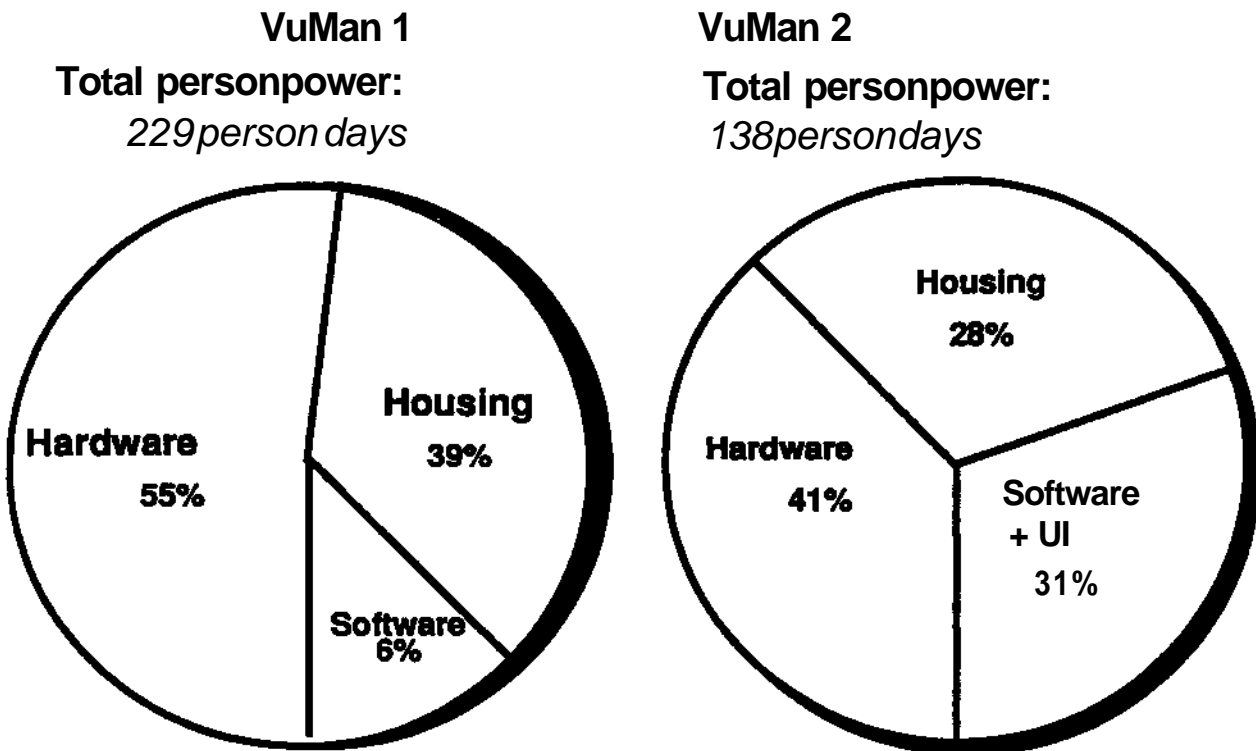


Figure 12 Personpower per discipline

Total personpower: 229 person days

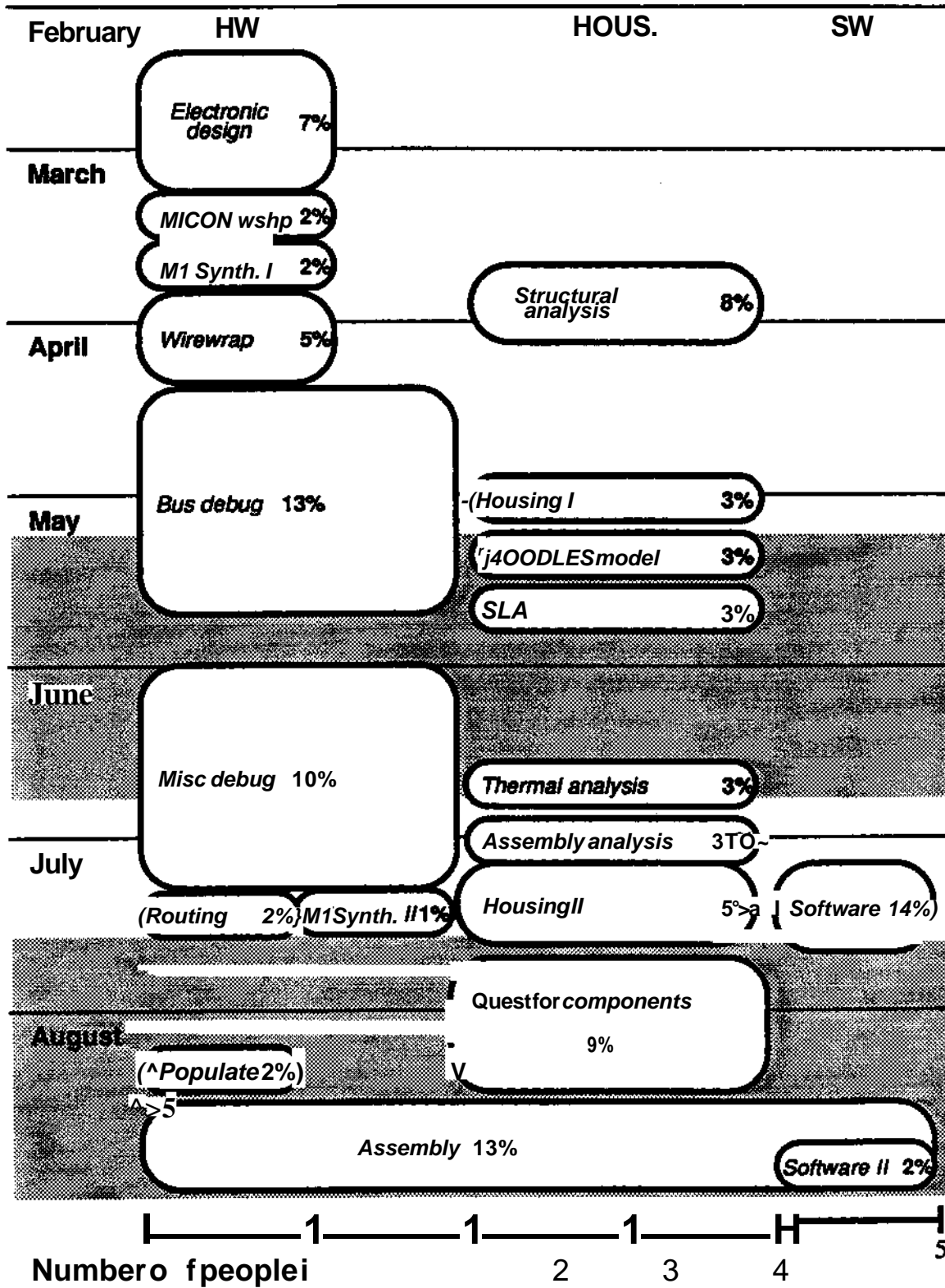


Figure 13 Design process and personpower for VuMan 1

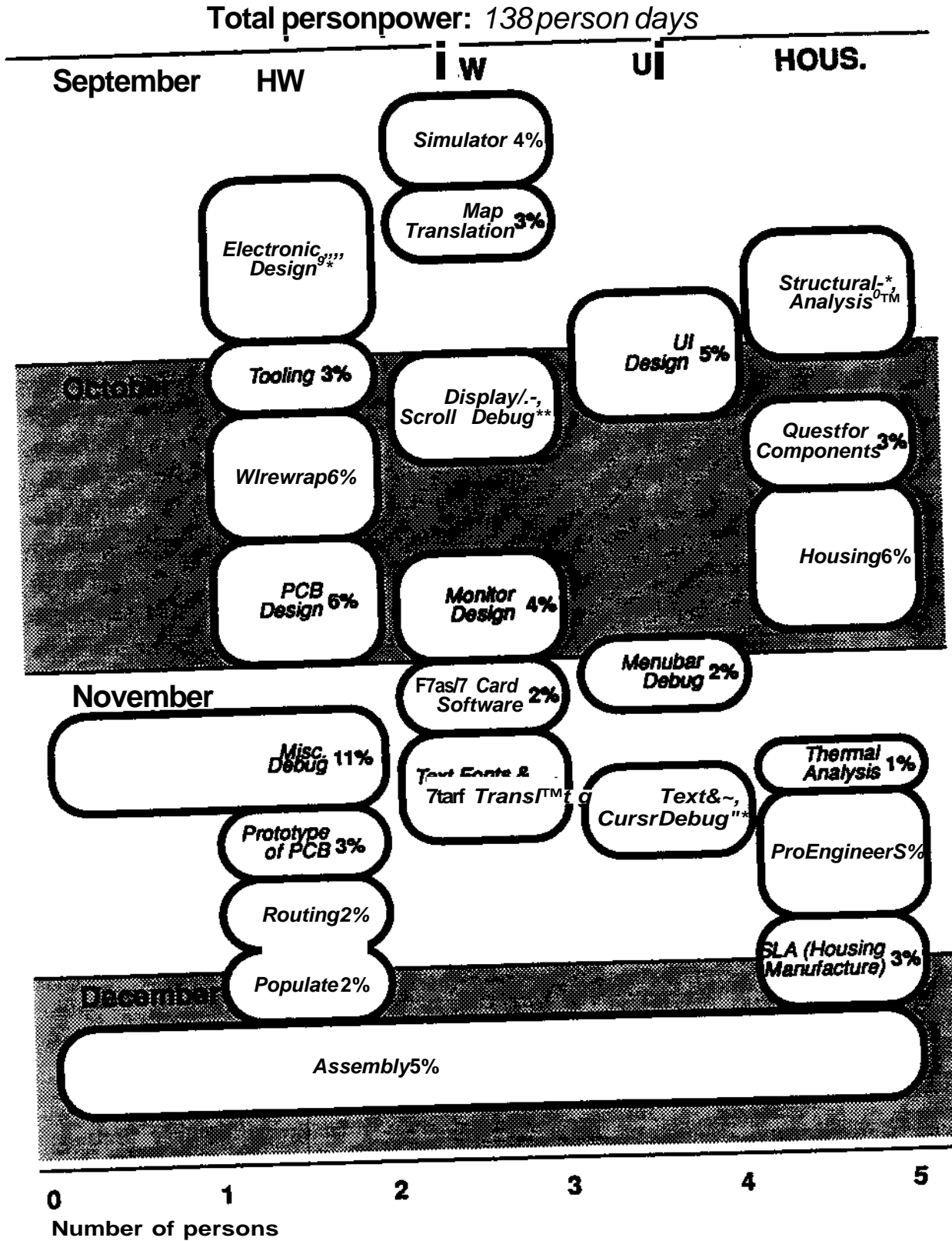


Figure 14 Design process and personpower for VuMan 2

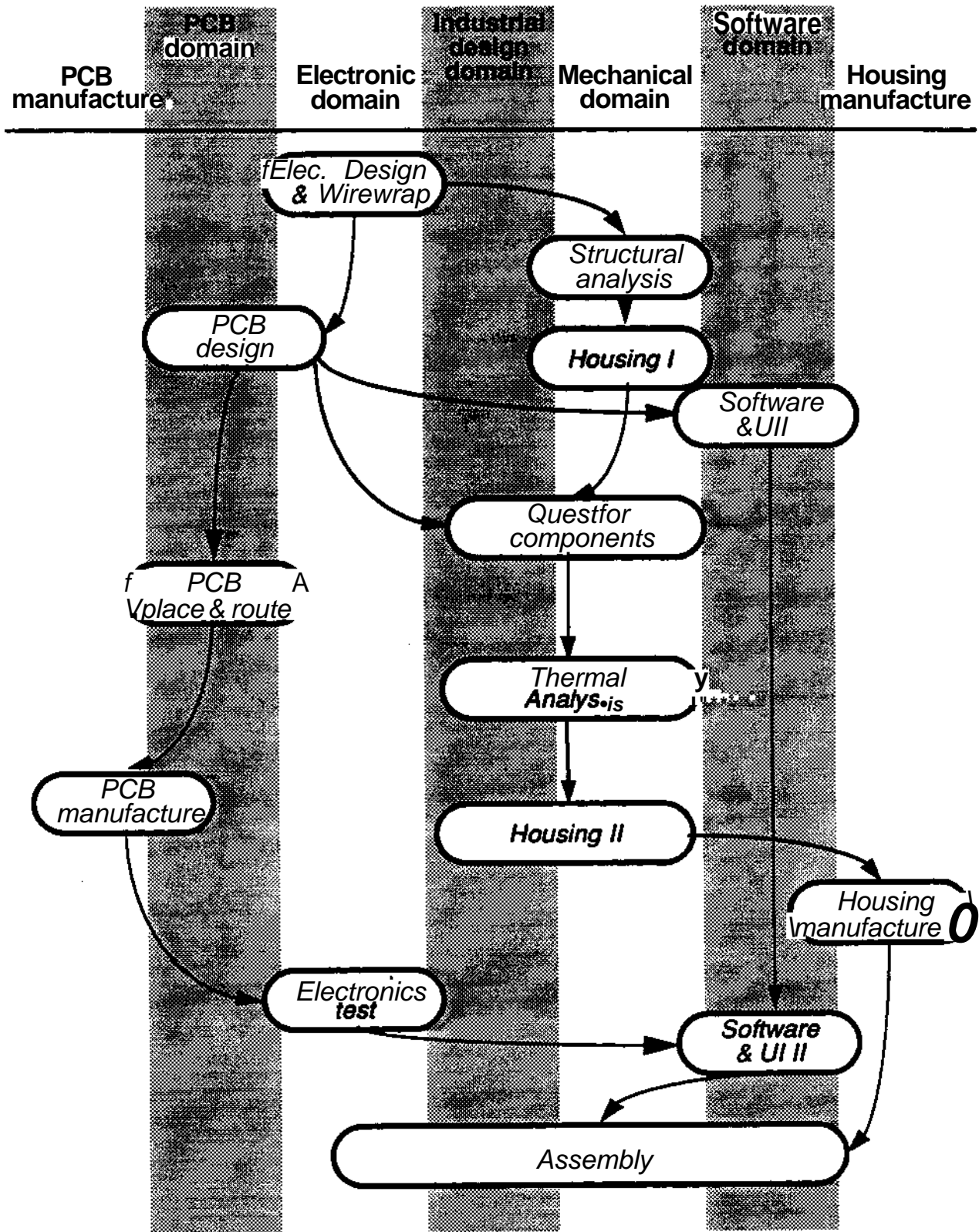


Figure IS Design task graph for VuMan 2

3.5 Comparison with other work

While there have been many publications on methodologies for system's design, few of these publications include data on actual design experiences. By providing data on concurrent activities, task dependency graphs, and distribution of effort we hope that other designers will be able to benchmark their efforts against those reported here. We estimate that the concurrent design approach did not appreciably increase the required personpower while decreasing total elapse time by a factor of three. The extra effort in research and breadboarding in the Technology Assessment phase, in early fabrication of functional/nonfunctional prototypes, in creation of software development environments independent of the target system, and in communications between all the disciplinary groups was more than off-set by the near error free design. Approximately 20% of the effort in design and fabrication of VuMan 1 was devoted to correcting mistakes due to miscommunication between the disciplines. There was no measurable lost time due to misunderstandings during the VuMan 2 project

A related question to the efficiency of the design process is the quality of the artifact produced by that process. Table 2 compares VuMan 2 to several commercial portable systems along several dimensions. The cost for VuMan 2 represents the purchase price of components in quantities of one plus the total cost of tooling for the printed circuit board divided among the seven units produced. Note that two thirds of the VuMan 2 cost is in the Private Eye display and the Flash Memory Card. The cost for commercial systems represents the sales price and includes manufacturing, distribution, documentation, and profits. Both general purpose and dedicated portable systems are depicted in Table 2 divided into three general cost categories: less than \$1000, \$2000 to \$3000, and greater than \$5000. VuMan 2 is competitive to the general purpose portable computers in volume, dimensions, power consumption, and functionality. VuMan 2 is also very competitive to the dedicated systems whose low manufacturing volume and the addition of speech recognition contribute to a higher cost.

3.6 Concluding Remarks

The design methodology described in this paper can be used in domains other than wearable computers. Communications about design decisions and identification of design dependencies were key elements of this design methodology. During the Technology Assessment phase, the various disciplines operated relatively independently, reporting to the entire group through periodically scheduled technology reviews. Several different communications mechanisms were used during the design phase including: group meetings, group presentations, reports, and electronic mail. An evolving design dependency graph was used to identify and resolve major design decisions. During the manufacturing phase, an evolving list of open issues and action items were used as a checklist. The checklist was updated at weekly design team meetings.

Future work in design methodology involves the automatic capture of the communication and design dependencies. The next wearable computer design will use n-dim. n-dim captures and formalizes the relationship between information which is modeled as a multi-dimensional space [8]. n-dim is based upon two observations about design, observations that are supported by experiences with the VuMan design process:

Table 2a. Comparison of VuMan 2 with commercial portable computers

Product	Class	Cost (US\$)	Volume (in ³)	Dimensions (in)	Weight (lbs.)	Processor/ Clock Speed (MHz)	Power Consumpt. (W)/ Batory Life (hours)
HP100LX	General Purpose	750	21.4	6.3x3.4x1	0.6	8086/8	low/ NA
VuMan2	Dedicated	1000	26.4	4x4.4x1.5	0.5	80188/13	1.1/ 3
Dell 320SU	General Purpose	2100	112	11x7.8x1.3	3.6	80386SL/20	24/ 3
Dell 325NC	General Purpose	2600	215	11x8.5x2.3	7.1	80386SL/25	NA/ 4
Vocollect Talkman	Dedicated	5000	24	4x6x1	2.0	68000/NA	NA/ 10
Refl. Tech. Mobile Terminal 220	Dedicated	8000	156	5.2x4.7x2.4+ 9x3x1.7+ 4.6x3.6x3.1	7.7	80286/NA	NA/ 10

NA - Not Available

Table 2b. Comparison of functionality of VuMan2 with commercial portable computers

Product	Functionality
HP100LX	<ul style="list-style-type: none"> • General-Purpose palm-top computer • 1 MB RAM • PCMCIA type II slot • Very small keyboard • 80 character by 25 line LCD display
VuMan2	<ul style="list-style-type: none"> • Menu-driven graphical display device • Private Eye Display (720x280) • 512 KB RAM • 1 to 20 MB Flash Memory • 3-button input
Dell 320SU	<ul style="list-style-type: none"> • General purpose Subnotebook computer • Non-backlit Grayscale VGA LCD display (640 X480) • 6 MB RAM (max of 10 MB) • 60 MB hard disk (max of 120 MB) • PCMCIA type II slot
Dell 325NC	<ul style="list-style-type: none"> • General purpose notebook computer • Backlit 16 color VGA LCD display (640X480) • 4 MB RAM (max of 12 MB) • 60 MB hard disk (max of 200 MB)
Vocoillect Talkman	<ul style="list-style-type: none"> • Speaker dependent, discrete-word speech recognition • Speech synthesis • No display • Dedicated to repetitive data-collection tasks • Optional radio link
Refl. Tech. Mobile Terminal 220	<ul style="list-style-type: none"> • 500 word speaker-dependent discrete word speech recognition • Private Eye display (720X280) • Operates only as a dumb terminal • Low bandwidth radio modem

- Progress in design is made by creating and refining a shared meaning of the requirements and of the potential solutions through negotiations, discussions, clarifications, and evaluations.
- Design efficiency is achieved through integration of information acquired from a variety of multi-disciplinary viewpoints.

4 Conclusions

In this paper we have highlighted a paradigm shift in the use of computing technology: wearable computers. The emergence of several key technologies is preparing the way for this paradigm shift in information processing from desk-top to portable hands-off computing. Portable hands-off computing superimposes information on the user's workspace, enabling the user to access information wherever it is needed. We consider the wearable computer to be an active part of the user's environment, where both user and computer are able to observe and potentially modify the environment.

The artifacts implemented at CMU help demonstrate the viability of this concept. VuMan 1 and 2 provide the user with maps, pictures and textual information on a small heads-up display. The interface enables the user to control the display of information in order to orient himself within the workspace.

In order to allow concurrent hardware and software development, we built software and prototyping tools, as well as a development environment. The hardware development occurred in parallel with the software and housing developments instead of the usual practice of sequential development.

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