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# The Smart Vest: Towards a Next Generation Wearable Computing Platform

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## Abstract

*Researchers engaged in the field of wearable computer study have been restricted by the packaging that houses computing, storage and communications resources. A new design for a platform is described that is integrated into and compatible with everyday clothing. Soft, comfortable and flexible, the Smart Vest is a lining composed of a lightweight mesh that serves as a medium for integrating electronic modules with flexible interconnections. The lining is a self-contained wearable computer supporting a wide variety of configurations. Advantage is taken of the low cost and small size of specialized silicon to provide a great deal of control over power consumption while adapting to the most efficient available bandwidth. The Smart Vest is intended to provide sustainable or "Green" operation by matching the use of appropriate silicon to the task of the wearer. It is worn on top of a shirt or undergarment and beneath a vest or jacket. The Smart Vest provides an improvement in comfort, configuration and concealment for the wearable computer user.*

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## 1. Introduction

Wearable computers may be designed to accommodate a variety of uses. The range spans single-function devices such as a communicator or remote control and extends into complex systems employing sensors, high speed processing and distribution along both local and wide area network connections [1].

Covering the functional requirements of this wide range of designs may be accomplished by establishing a new chassis that supports wearable-computing research in the present and everyday use in the future. A goal was set that such a wearable computer should be "softer" than the part of the human body on which it lays, so that it can be worn with comfort. The components that form the wearable system should be invisible and not interfere with everyday clothing. At this level of integration between the worlds of fashion and technology, the issues involving configuration, service and user interaction become interesting. Different classes of processor, functional device level sub-systems, communications, interconnections, power systems and storage must be supported with minimal attention given to these items by the user.

It is now possible to design a wearable with these guiding principles in mind: Silicon is free, power is expensive and there is no silver bullet for bandwidth. The use of heterogeneous silicon to accomplish most if not all wearable computer applications adds little or no cost in proportion to the rest of the wearable system. By matching the required function with the appropriate components and using only the bandwidth needed for each specific operation, power is conserved and available bandwidth is utilized effectively. Power has a cost and burden associated with it now and in the foreseeable future. The availability of bandwidth for the wearable user in the next few years is not guaranteed nor is the cost of service known. It is therefore prudent to design wearable computers that are based on conservation of both power and bandwidth while relying on the ever shrinking size and cost of silicon to achieve a sustainable system.

Preferably, little or no modification should be required by the user of such a system except for the act of configuring by the addition or subtraction of components required for the desired functions. This configuration should be no more difficult than selecting and putting on a pair of socks.

Today, such configuring is performed using PC cards, smart media, compact flash, USB, serial, parallel and video ports. Docking stations and device bays provide additional configuration choices and the latest in portable devices such as cell phones and palm pilots allow for accessories to be plugged and shoed for additional features. However, these are external configuration changes performed at arm length on a device outside of the users clothing [2]. The wearable computer of the future should have the ability to be worn underneath or within the layers of the wearer's clothes. This makes for some interesting configuration issues.

Let us proceed for the moment with a vision of wearable computing that contains an inner chassis with the essential components. These components would include computing power, communications, storage, I/O and control to get us around during the day and an external configuration method employing objects in the shape of buttons, fashion accessories, pocket docking devices and hidden strips, such as thin handset strips that fit under lapels.

Advances in electronic technology and manufacturing techniques have provided the wearable researcher with many components and tools that may be combined to construct a variety of wearable computers [3]. While these are useful computing platforms sporting high performance, low power consumption, flexibility and ease of configuration, these platforms are essentially rectangular and solid. Therefore the physical mounting of the electronics is usually on top of and outside of the clothing worn by the researcher. The use of shoulder slung bags, belt worn chassis and backpacked notebook computers is the predominant layout for today's wearable researcher.

The use of cables to connect devices to the wearable computer creates an unusual and somewhat unattractive appearance to the wearable. Efforts have been taken to integrate costumes and fashion accessories to give a futuristic style to the outfit [4] and research has shown that it is possible to fabricate electronics into jackets using conductive thread [5].

This paper describes ongoing research into the using a lining in the shape of a vest as an electronic chassis. This vest shaped lining can be worn between layers of clothing. This allows the vest to become an improved platform for wearable computing.

## 2.0 Design Principles

We started with these guiding principles: Softer than the body (no pinching or poking!), silicon is cheap and can be used generously, power is expensive and burdensome and finally there is silver bullet for the problems of bandwidth. Preferably, this should be a one piece, single chassis that can be put on and taken off with ease. There should also be a method provided for servicing and customizing the system in a manner similar to the way people tend to dress themselves on a daily basis.

Starting from these design considerations, we have developed the following approach to wearable computing.

## 2.1 Baseline Chassis

Current devices available for wearable computer use run the gamut from pocket sized hand held PDA to PC104 modules [6] to high performance graphic workstations carried in backpacks. One system uses a flexible design that follows the contour of the body [7]. When these devices are worn outside of the user's clothing, they are accessible during the period of use. This allows for the re-configuration of the system, swapping of power sources and access to internal switches.

To move the electronics underneath the outer layer of clothing requires the system to become more or less fixed in its physical configuration [8]. This leads to configuration made in advance of the user's completion of dressing and severely limits any changes that can be made during the day. Although it is possible to utilize external devices such as sensors, switches, displays, handsets, network interfaces and power sources, it is preferable to place as much of the system inside of the clothes.

A chassis design for the internal components must account for enough capability to support an average day or evening of service in support of a number of baseline wearable computing functions.

Configuration would take place in the morning, when the user dresses for work and in the evening, when the clothing is reconfigured. On weekends, similar transitions can occur between recreational and fashionable attire. It is the intention of this work that system reconfiguration occur and compliment the act of dressing and changing clothes.

Target outfits for the Smart Vest include vest for warm weather and casual attire, jacket for cold weather and more formal dress and a sash for use in developing nations and rural areas where western attire is not considered appropriate.

## 2.2 Heterogeneous Silicon and Power

As the wearable computer is carried around during the day, certain functionality is expected to be readily available without depending on external resources. Examples of this are IP Telephony, Location, Messaging, Internet Connectivity and Software Agents. To perform such functions in a dependable manner requires that power be available. If the power requirements of the system are not kept to a minimum, the power source will become too heavy and bulky to meet the packaging goal of a somewhat invisible system.

Typical methods for power conservation include:

1. Reliance on low power devices.
2. Software control of devices and clocks.
3. Sleep and Standby Modes

Most people only use methods 2 and 3. We believe that silicon is now cheap enough that the most significant additional power reduction can be achieved by using a number of different devices to perform functions for which they are matched. For example, a 120 MHz Mobile Pentium processor running at 5 watts is not a good device for performing GPS sensor data acquisition, text message display or E-mail composition. These can be easily handled by an embedded RISC such as that found in Palm Computers.

By using such a low power device as the host controller for the system, a low power core function can be provided to the user wearable computer while maintaining the ability to "Power Up" the rest of the system in part, as needed.

When high performance computing is desired for actions requiring graphics, image processing and mathematics, the use of DSP and SIMD processors are available in low voltage core suitable for use on demand. Multi-Chip Modules or MCM present one method of shrinking the package size [9]. These would be interconnected with the core block using a variety of methods. USB, RS-232 and Ethernet make useful bridges between devices and fiber optics may be used provided that a low power scheme is available.

The use of context awareness is a powerful tool for determining what devices are needed according to what the user in engaged in or in anticipated of an event. Recent advances in this area of wearable computer research have demonstrated a very useful ability to determine the computer's mode of operation based on user's environment [10].

Where extended use of high performance applications is required, a computing resource such as a single board computer can be carried along or approached indoors and accessed using a wireless network at 11 Mb/s.

## 2.3 Bandwidth

While a wireless network is the connection of choice and low power embedded communications controllers such as Bluetooth are expected to be employed in the near future, when the wearable computer is away from such supporting infrastructure, there is no practical alternative to the low speed Cellular Modem. Data rates of 9600 b/s are not very interesting but do provide for a number of core functions as described above. Therefore it is prudent to supply a Multi-band radio communications system employing high speed 802.11, Bluetooth and CDPD/GSM.

Likewise, the application of the GPS is limited to outdoor use with a clear view of the sky. Combinations of additional systems such as fixed indoor identification beacons, sound and image cues, and inertial motion should be employed. These can be used to steer the wearable system into the correct mode of operation to adjust for available resources and expected tasks.

## 2.4 Other Considerations

Areas where the Smart Vest will have external components include displays, cameras, keyboard, telephone handset, infrared transceivers and external power sources.

Eyeglass Displays with micro displays and cameras would be connected using a decorative rope that extends from the stem of the eyeglasses and connects to a snap on the inside of the garment near the neck. Appropriate safety considerations would include a breakaway cable in the event of the cable becoming snagged.

Keyboard entry through use of a chording keyboard, freehand mouse or fabric buttons would be attached through special snap connections hidden into the garments.

Thin hidden telephone handsets that tuck away into a pocket or collar can be supplemented by a speakerphone using flat panel speaker technology and phased array microphones integrated into fabric and attached to the lapel.

Infrared capability can be a useful addition to the wireless components. This will most likely require a small pop-up component probably around the shoulder or neck area.

External power will be used for recharging as well as direct power of the system. One method to accomplish this may be the use of contacts that can be mounted or clipped onto the sleeves for intermittent power pickup from chairs. Another method may employ breakaway contacts that plug inside a pocket. For outdoor daytime use, amorphous flexible solar panels can provide for extended battery life between charges at the expense of changing the appearance of the clothing.

## 3.0 Design Approach

Our initial approach was to consider function, aesthetics, comfort, versatility, and feasibility all at once. After experimenting with different approaches it became evident that producing a vest that would provide the basic platform on which the solutions to other problems could be studied, was the most expedient direction to take. This was accomplished with plastic-coated webbing sewn into a minimal vest with pockets placed at anticipated module and battery locations.

Concern for natural body contours once modules were in place was then addressed. A number of concepts were tried and proved to be too rigid to produce a natural appearance. Weight was a consideration when adding any contouring material, as the basic vest with components proved to be so comfortable as to make one not aware, after a short while, of wearing it. Work on this consideration is in progress.

One-size-fits-all seems to be a workable approach for the initial models, since the vest was tailored using a female form; however, we may want to accommodate the 90th percentile with a larger version.

## 3.1 Construction

The Smart Vest must be comfortable to the wearer and as visually undetectable as possible to onlookers. An even distribution of components along the upper body would have the effect of increasing the wearer’s appearance by 1 size. This would allow for the placement of modules along portions of the shoulder, chest, sides, mid section and lower back. The modules are attached to a thin, lightweight lining. A detachable module with an embedded processor card is shown in Fig. 1.

## 3.2 The Lining

The key to the inner construction that is compatible with daily use is a lining made of a plastic mesh. This mesh provides for circulation of air, even distribution of weight and an integrated wiring path by weaving the wires within the mesh.

Plastic-coated net is the selected material for use as the vest material. This proved to have the proper tenacity for weaving wires, sewing Velcro, etc. It also exhibited excellent weight and strength characteristics needed to support the modules. The course weave and large gaps between strands of plastic allowed for adequate air circulation to prevent accumulation of heat and moisture. Many other fabrics were considered at this point and discarded.

Latex rubber sheet became the initial material used for pockets in vest. The intent was to keep a flat outer contour. Components in the pockets could vent upwards through the opening at the top and also breath through the mesh towards the inside. There was an additional use found in forming resilient transitions between modules on shoulders.

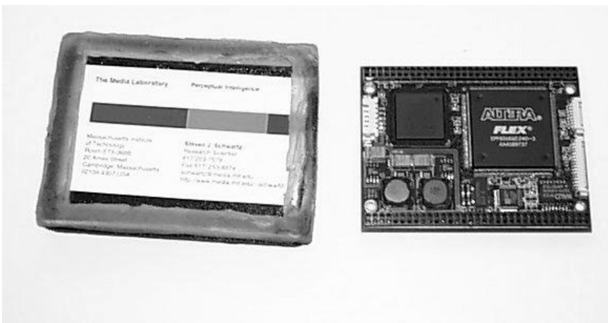


Figure 1: A Smart Vest soft packaging module and embedded Power PC plus FPGA is shown with a business card for size.

### 3.3 Modules

The modules are designed to have attachment points to the mesh and rely on external flat high-density connections. Initial circuit design has incorporated small credit card sized computers interconnected with devices such as PCMCIA wireless LAN, Palm Computer and GPS.

Soft on the inside and hard on the outside. This is what we set out to accomplish and best describes the most important performance characteristic placed upon the design of the modules. Many combinations of materials were experimented with to achieve this and what follows are some of our observations.

Urethane rubber was then used for the entire shoulder module. This was molded into a complete front to back shoulder pad and provided contours that worked quite well for blending the module into the shape of the body. The outer garment showed no bunching or edges. Unfortunately, these modules weighed too much for practical use.

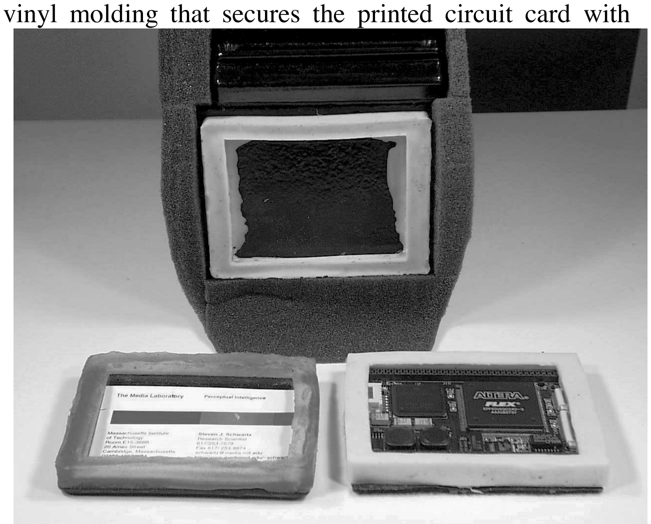
Silicone RTV rubber was used to form the outer edge of the circuit card. Although it held the card in place this proved to be a bit too rigid for contouring. The edges of the modules were easily observed through clothing and they had a tendency to bunch up the fabric around the edges.

Vinyl was then substituted for the Silicone RTV rubber as a retaining edge on the module. This vinyl was heated carefully to change the characteristic of the material and give it a soft Jell-O like texture. It is exceptionally soft and conforms easily to the shape of the outer garment. It is the most successful material tried for this application. Care was used to prevent over-heating during the preparation for molding

ABS plastic was tried for forming a protective outer cover for the components. This proved to be too rigid for a natural look for shoulder placement. A decision was made to go without a cover for the first prototype.

Styrene plastic is the material finally employed as a substrate to bind to the molded vinyl. Velcro is applied to the underneath side of the substrate to attach modules to vest. Cyanoacrylate Ester known as "Super Glue" was used as a bonding agent. A variety of modules using different materials are shown in Fig. 2.

Figure 2: Modules made with vinyl, silicone or foam.



The module used for this first Smart Vest prototype uses a vinyl molding that secures the printed circuit card with molded groove around the edge. This is glued to the styrene substrate and uses a Velcro base for attachment to the mesh lining.

The first version is square in shape when held in the hand but easily compresses to partially fill the gap between the outer garment and the lining. This reduces the appearance of the module when worn under an outer garment. Placement of the modules is designed to avoid parts of the body where the module would place pressure in a single point. The mesh lining, Velcro support and flexible base of the module all work together to create a soft, comfortable feel.

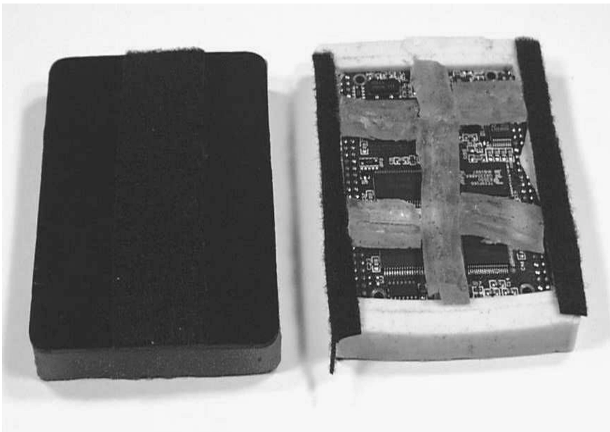


Figure 3: Left uses vinyl on styrene substrate. Right uses Silicone RTV on vinyl with no rigid base.

The underside of two modules is shown in Fig. 3. The left base is composed of styrene with Velcro running through the center while the right base is composed of soft vinyl with Velcro attached to the outside edge of the more rigid silicone rubber.

### 3.4 Layout

Starting at the top, both shoulders employ Class 1 modules designed to hold processor boards. These can include host controller (core device), processor, bus interface, image capture, display and other high-speed devices.

Shoulder module containing the processor or core unit Heat from these devices will escape through the top of the garment at the shoulder and through the sleeves. A close-up of the shoulder module attached and wired into the mesh is shown in Fig. 4.


Figure 4: Shoulder module wired into mesh lining.

Around the area where shirt pockets are usually found, the Class 2 modules are located. They are used for radio electronics such as wireless LAN and Cellular Modem on the right side and a combination of solid state and rotating storage on the left side.

On the bottom 3 inches of the lining is a 320-degree pocket open at the front and circling the back. This is the location of the batteries. Lithium Polymer batteries are the preferred source of power. Their lightweight, pre-formed shapes allow for 1” x 2.5” strips to be interconnected for maximum flexibility. Every other space will be open for low power applications. An additional layer of battery may be loaded to increase capacity. Battery weight is expected to be between ¾ - 1.5 lb.

### 3.5 Wire Harness

Ultra flexible Multi stranded copper wire is used to weave the interconnections into the lining. 28, 30 and 36 gauge wire with up to 25 strands each with very thin vinyl insulation.

### 4.0 First Prototype

The first computer system constructed was a wireless web site. This was chosen for testing a full set of features including complexity, user interface, network connectivity, reliability, power requirements, heat dissipation, multi-user load and ease of use. Fig. 5. shows a complete smart vest containing (2) processor systems on each shoulder, network connection and battery power.

Figure 5: First Smart Vest constructed with twin processors, network connection and battery power.

The computer chosen for the Class 1 module was an Embedded Power PC. This 3x5 double-sided 7-layer card uses a Motorola 823, 16 MB DRAM, Ethernet, USB, Serial ports and an Altera 6K Flex FPGA set up as an ISA bridge. This electronics package is shown in the shoulder module worn over a shirt in Fig. 6.

Figure 6: Embedded processor card integrated into Smart Vest and worn over a shirt.

Embedded Linux was chosen as the OS to allow for customization of the kernel to fit compressed within 2MB of on board flash. The computer would boot from flash and start Apache web server and access network files for its web pages. For the first test, the MIT wearable web site was used [2].

Although initial testing used a direct Ethernet connection to demonstrate core functionality, a Lucent Wavelan wireless LAN card is being tested in conjunction with a Cirrus Logic 6722 ISA to PC Card bridge. The Smart Vest worn underneath a leather vest is shown in Fig. 7.

Power consumption for the initial test was 2 watts nominal with a peak of 2.5 watts during boot. The system ran for over 6 hours on 4 ounces of lithium batteries.

Figure 7: Author wearing the Smart Vest with a leather vest suitable for summer or casual wear.

## 4.1 Current Progress

It is intended to branch out and enhance the initial effort in two directions. First, it is essential to deploy the functionality described above. This requires additional electronics and a shift from conventional chipsets to a virtual interface using FPGA and devices suitable for multi-functions to allow for rapid reconfiguration of the system without user intervention. Second, the modules must become even more compact and body sculpted.

This will demand a transition from rigid printed circuits encased in simple molded compounds to a hybrid of components mounted on rigid substrates that are bonded to a flexible, impedance controlled interconnection.

Each module then becomes a body conforming part. An example of this would be a processor chip in a Ball Grid Array package attached via flex to the memory chips & flash, bus interface FPGA, transceivers & power supply. This would be a 20 – 50% increase in footprint but the shape and flexibility would make the module even more comfortable with greater fit. A wire harness typical of those used in wearable computers is shown in Fig. 8. The same harness constructed with flex circuit and low profile connectors is shown in Fig. 9.

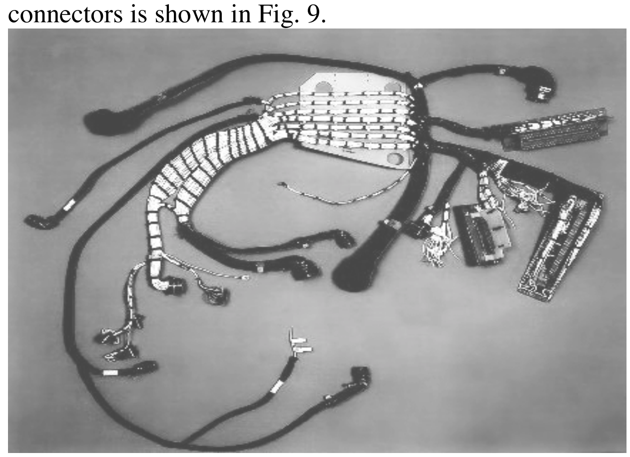


Figure 8: Wire harness typical of those used in wearable.

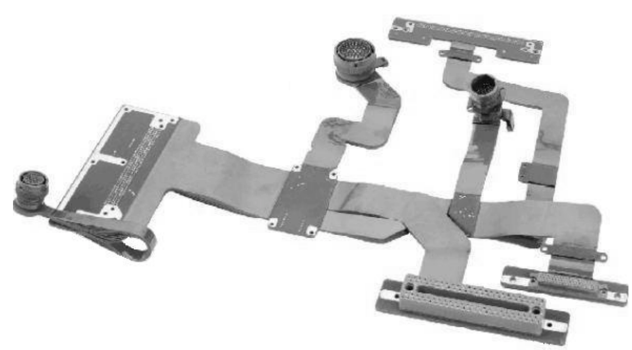


Figure 9: The same harness constructed with flex circuit and low profile connectors.

As the modules become more advanced, there will be a requirement for internal heat pipes [11], shielding and integral wire harnesses. These will consist of a combination of flex circuit tail for subtle curves and discrete wire for joints where maximum flexibility is required [12].

Experimentation with the external configurations will begin when the first fully functional lining is completed in the fall of 1999. The first items scheduled for external configuration are lapel buttons that modify use of radio spectrum and bandwidth.

## 5. Conclusions

It is possible to design and build wearable computers that are soft and comfortable while providing the wearable researcher or end user with a sustainable system for daily use. Such a system can be worn daily and perform the operations required of wearable computers without compromising the look and appearance of everyday clothing. The low cost and size of silicon is leveraged to provide a reduction in power consumption and mitigation against lack of widely available low cost bandwidth.

Configuration issues become minor additions to the everyday ritual of dressing or changing outfits to match activities.

Figure 10: The author is shown wearing an Armani suit jacket with the Smart Vest. The Smart Vest is operating as a web server running entirely from flash and maintains operation for 6 hours using 4 ounces of lithium batteries.

The first Smart Vest has been in operation since early Spring 1999. The comfort, appearance and performance achieved have proven that such a wearable can be realized. Additional Smart Vest prototypes with increased features are in the design stage. Increased use of low power sub-micron silicon, FPGA, multiple bus interfaces and wireless devices will provide for a wearable computer that is compatible with everyday living as well as support the demands of research in this field.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