# The Wearable Motherboard: A Framework for Personalized Mobile Information Processing (PMIP)

Sungmee Park
School of Textile & Fiber Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
+1 404-894-6529
sungmee.park@tfe.gatech.edu

Kenneth Mackenzie
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332
+1 404-894-1704
kenmac@cc.gatech.edu

Sundaresan Jayaraman[1]
School of Textile & Fiber Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332
+1 404-894-2490
sundaresan.jayaraman@tfe.gatech.edu

## ABSTRACT

Textiles and computing share a synergistic relationship, which is being harnessed to create a new paradigm in personalized mobile information processing (PMIP). In this paper, we provide an overview of this "interconnection" between the two fields and present the vision for "E-Textiles," which represents the convergence of the two fields. We discuss the role of the Georgia Tech Wearable Motherboard in pioneering this paradigm of "fabric is the computer" and serving as a framework for PMIP. Finally, recent research in this area resulting in the realization of a "computational *fabric* network" is discussed.

## 1. TEXTILES & COMPUTING

John Kay's invention of the flying shuttle in 1733 sparked the *first* Industrial Revolution, which led to the transformation of *industry* and subsequently of civilization itself. Yet another invention in the field of textiles – the Jacquard head by Joseph Marie Jacquard (*circa* 1801) – was the first *binary information processor*. At any given point, the thread in a woven fabric can be in one of two *states* or positions: on the face of the fabric or on the back. *Pattern* cards were punched or cut according to the required fabric design. A hole in the card signified that the thread would appear on the face of the fabric, while a blank meant that the end would be left down and appear on the back of the fabric. The Jacquard head was used on the weaving loom or machine for raising and lowering the *warp* threads to form desired patterns based on the *lifting plan* or *program* embedded in the cards. Thus the Jacquard mechanism set the stage for modern day binary information processing.

Ada Lovelace, the benefactor for Charles Babbage who worked on the Analytical Engine (the predecessor to the modern day computer), is said to have remarked, "The Analytical Engine weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves." The Jacquard mechanism that inspired Babbage and spawned the Hollerith punched card has been instrumental in bringing about one of the most profound technological advancements known to humans, viz., the *second* Industrial Revolution also known as the Information Processing Revolution [1]. In fact, when Intel introduced its Pentium class of microprocessors in the 1990s, one of the advertisements had a "fabric of chips" emerging from a weaving machine; this picture eloquently captured the essence of chip making – a true blending of art and science – much like the design and production of textiles!

More recently, the design and realization of the Georgia Tech Wearable Motherboard represents a significant advancement in the integration of textiles and computing paving the way for the paradigm of "fabric is the computer" [2, 3].

## 2. THE E-TEXTILES VISION: "FABRIC IS THE COMPUTER"

Figure 1 depicts the vision for "E-Textiles" or the paradigm of "fabric is the computer." The major facets illustrate the various "building blocks" of the system that must be seamlessly integrated to realize the vision, starting with the underlying physical fabric or "*Platform*." The design of this platform or infrastructure involves the exploration of materials, structures and manufacturing technologies. The second key facet for realizing this paradigm of a true computational *fabric* is the "*Interconnect Architecture*" in the fabric, which involves the design and incorporation of physical data paths and interconnection technologies, i.e., the realization of "textile electrical circuits." Integration of sensors, microchips and other devices (e.g., for communication and control) is critical for the realization of an "intelligent" E-Textiles for *any* application, say for example, battlefield management, and therefore, "*Hardware Integration*" constitutes the third facet or building block shown in Figure 1. Issues related to information processing such as fault tolerance in light of manufacturing defects and Quality of Service (QoS) *within* the E-Textile and *between* the E-Textile and external agents/devices are critical for the incorporation and optimal utilization of computing resources, and therefore, "*Software*" is the fourth facet of the E-Textile continuum. And finally, as shown in the figure, a set of underlying *performance metrics* ranging

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[1] To whom correspondence should be addressed.

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from the physical dimensions (of the resulting structure/system) to costs, manufacturability and data flow rates must be utilized to assess the successful realization and performance of the desired E-Textile. Thus this paradigm of "fabric is the computer" represents a fascinating area of research that fosters, nay necessitates, collaboration amongst scientists and engineers from a variety of disciplines including textiles, computing and communications, sensor technologies and application domains (e.g., medicine, space, military).

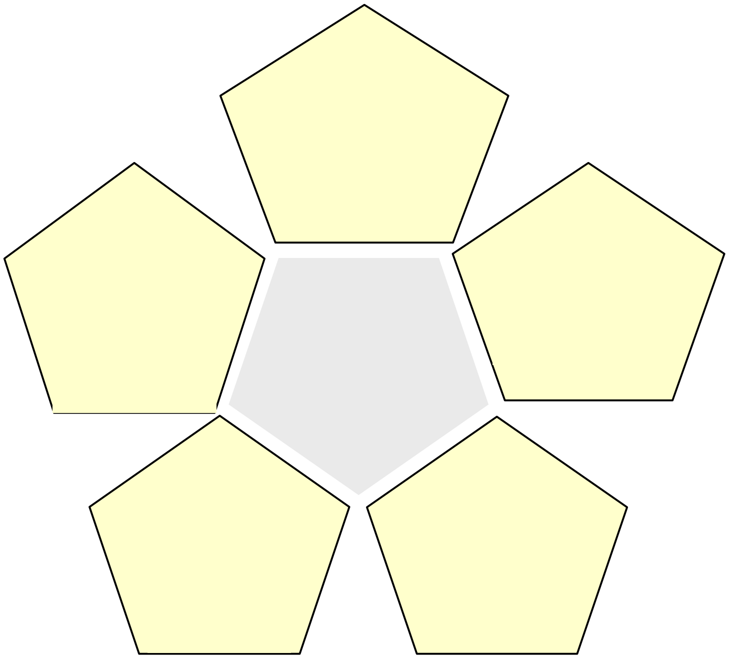

**Figure1. The E-Textiles Vision**

## 3. THE WEARABLE MOTHERBOARD

The Georgia Tech Wearable Motherboard (GTWM) provides an extremely versatile framework for the incorporation of sensing, monitoring and information processing devices. It uses optical fibers to detect bullet wounds, and special sensors and interconnects to monitor the body vital signs of individuals. The principal advantage of GTWM is that it provides, for the first time, a very systematic way of monitoring the vital signs of humans in an *unobtrusive* manner (Figure 2). Appropriate sensors have been "plugged" into this motherboard using the developed Interconnection Technology and attached to any part of the individual being monitored, thereby creating a flexible wearable monitoring device. The flexible data *bus* integrated into the structure transmits the vital signs information to monitoring devices such as an EKG Machine, a temperature recorder, a voice recorder, etc. The *bus* also serves to transmit information *to* the sensors (and hence, the wearer) from external sources, thus making GTWM a valuable information infrastructure [3]. GTWM is lightweight and can be worn easily by anyone -- from infants to senior citizens.

**Figure 2. Georgia Tech Wearable Motherboard**

Although it started off as a "textile engineering" endeavor, the research has led to an even more groundbreaking contribution with enormous implications: the creation of a *wearable integrated information infrastructure* that has opened up entirely new frontiers in personalized information processing, healthcare and telemedicine, and space exploration, to name a few [4]. Until now, it has not been possible to create a personal information processor that was customizable, wearable and comfortable; neither has there been a garment that could be used for unobtrusive monitoring of the vital signs of humans on earth or in space. A Special Issue of LIFE Magazine entitled *Medical Miracles for the Next Millennium* (Fall 1998) featured the Smart Shirt as one of the "21 Breakthroughs that Could Change Your Life in the 21st Century" thus clearly demonstrating the potential impact of the Wearable Motherboard technology on humans in the next century.

## 4. ADVANCING THE PARADIGM: RECENT RESEARCH

While the interconnection technology in GTWM facilitates the "routing" of information (i.e., signals) from any point to any other point on the wearable motherboard, the data paths are pre-determined. To realize the concept of a "programmable" computing device as an *integral* part of the fabric/garment in which "the fabric is the computer," there is a need to design and develop the *architecture* for the wearable motherboard that would seamlessly integrate the hardware, software and softw*ear* (fabric/garment) components or building blocks of the system. Such an architecture will facilitate the real-time reconfiguration of the system ‘building blocks’ that would lead to the realization of a truly adaptive and responsive wearable computational fabric system thus resulting in *pervasive/invisible* information processing.

Research is being carried out to explore the feasibility of creating such an E-Textile to demonstrate PMIP using the wearable motherboard. As the first step, the information from one or more sensors (e.g., electrocardiogram or voice) is being routed through the “soft” interconnects in the fabric to the desired output points using FPGAs (field-programmable gate arrays).

## 4.1 The Approach

A "switchbox" approach has been chosen to combine the conductive fibers of an E-Textile into a programmable network. The switchbox approach is to treat the conductive fibers like the wiring resources in an FPGA to which switching components can be added at strategic intersections. A key problem in the switchbox architecture is to tolerate loose manufacturing tolerances since it is not known in advance as to which wires are connected to which pins on the switchbox. Therefore, we suggest a design for a single-chip, integrated switchbox and, simultaneously, build a demonstration prototype using off-the-shelf components.

## 4.2 The Architecture

The architecture consists of conductive fibers in the fabric plus switchboxes, which are affixed (like buttons) atop intersections of the fibers. The architecture leads to three decisions [5]:

1. Placement of switchboxes;
2. Complexity of wiring; and
3. Complexity of switchboxes.

### 4.2.1 Placement of Switchboxes

The manufacturing tolerance for placement of switchboxes can be tight or loose.

a. Exact: switchboxes placement tolerance could be good enough to place switchbox contacts atop particular conductive fibers. This option requires precise manufacturing tolerance or a large fiber-to-fiber pitch.

b. Close: the placement tolerance is a small factor larger than the fiber pitch.

c. Random: switchbox placement is uncontrolled.

Since one of the overall objectives of this research is to produce such E-Textiles in a typical manufacturing environment, option (b) has been chosen since it is similar to fastener placement in apparel manufacturing. We assume that a switchbox covering several fibers can be placed such that it will contact a particular fiber but we do not know which switchbox contact will actually make the contact.

### 4.2.2 Complexity of Wiring

The conductive fibers in the E-Textiles can be continuous or cut at each switchbox.

a. Continuous fibers are easily manufactured.

b. Cut fibers lead to a richer interconnect with higher local bandwidth between points in the fabric.

From a manufacturing standpoint, option (a) is easier and so fibers (yarns) that are continuous in the fabric have been chosen. We address restricted bandwidth by making the switchboxes more capable.

### 4.2.3 Complexity of Switchboxes

Switchboxes can be built at multiple "grain" sizes, i.e., how much computing resources are concentrated at the intersection of two fibers. We distinguish grain sizes based on the extent to which the switchbox component participates in topology discovery and configuration.

a. Minimalist, e.g., a single transistor or gate at a single intersection: configuration is managed and performed externally although configuration state may be stored at the intersection, e.g., using technology analogous to floating gates in VLSI.

b. Communication-capable: the switchbox can communicate with, and perform local configuration on behalf of, an external agent. Global configuration is managed externally.

c. Self-configuration-capable: the switchbox contains enough processing power to participate in a distributed, global configuration algorithm.

We chose option (b), switchboxes capable of self-configuring to the point of establishing communication with an external agent which then manages global configuration.

Thus, we chose an architecture for the computational fabric in which the electronic elements are of moderate capability, are placed deliberately, but inexactly, and without making cuts in the fabric.

## 4.3 Technical Issues and Decisions

We have identified three key issues with our architecture and proposed solutions for them. They are: power distribution, configuration information distribution and automatic discovery of topology.

### 4.3.1 Power Distribution

Power distribution is difficult with inexact placement of components because power connections are usually distinguished from signal connections. We believe it may be possible to power ordinary integrated circuits via any pin using diode structures similar to existing static discharge protection structures. However, for the first demonstration prototype, we use distinguished power wires in the fabric by providing enough spacing to account for our placement tolerance (unlike signal wires).

### 4.3.2 Configuration Information Distribution

Configuration information distribution is similarly difficult because FPGAs and microcontrollers typically expect configuration information to be presented on specific pins. This problem is not fundamental, however. We use an FPGA-within-an-FPGA technique to address the problem: we use a statically-defined FPGA that includes configurable elements within it. Thus we can emulate an FPGA that accepts configuration information from multiple (initially any) pins.

### 4.3.3 Discovery of Topology

Topology discovery can be externally or internally managed and sequential or parallel. We adopt a conservative approach: an external agent sequences the discovery and the discovery proceeds sequentially from the element nearest the external agent.

## 4.4 Realization of the Architecture

The first step in realizing the architecture through a prototype demonstration has been to define an ideal switchbox element that we believe is buildable using current technology. The next step is to begin prototyping an approximation to the ideal device to serve as a proof-of-concept.

The ideal device is an EEPROM-based FPGA in a custom plastic package that contains insulation-displacement-style connectors instead of pins. The device would be press-fit onto the fabric like a fastener. Once configured, the device would provide digital communications between points on the fabric including sensors, effectors and communications devices that attach to the switchboxes or directly to conductive fibers that cross a switchbox.

The prototype device is a 2.8"x1.8" protoboard containing a small EEPROM-based FPGA (Altera EPM7160S) plus a microcontroller (Motorola HC11) as shown in Figure 3. The board connects to the fabric using two standard 26-pin insulation-displacement connectors (IDCs) ordinarily used for ribbon cable.

The fabric in Figure 3 contains conductive fibers at a density of 10 per inch. The 26-pin IDCs contain contacts at a pitch of 20 to the inch. We find that every fiber makes contact with some contact in the connector but the position of that contact is off by up to two positions in the connector. In the connector, the leftmost and rightmost fibers are dedicated to power buses while the center fibers carry signals, up to seven signals in each direction.

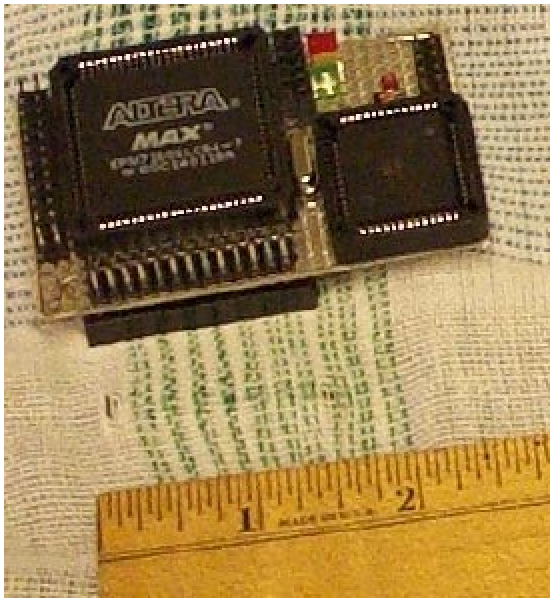

**Figure 3. Prototype board, 2.8"x1.8", containing the FPGA and microcontroller. Site-specific sensor/effector/communication devices attach as "daughtercards."**

The chosen FPGAs were physically integrated into the fabric (see Figure 4). Software was developed to demonstrate the "in-fabric" network. One of the FPGAs communicated with an external agent (a Linux-based personal computer) that was responsible for managing the global configuration of the FPGAs in the fabric by sequencing the "discovery" in the fabric beginning with that initial FPGA.

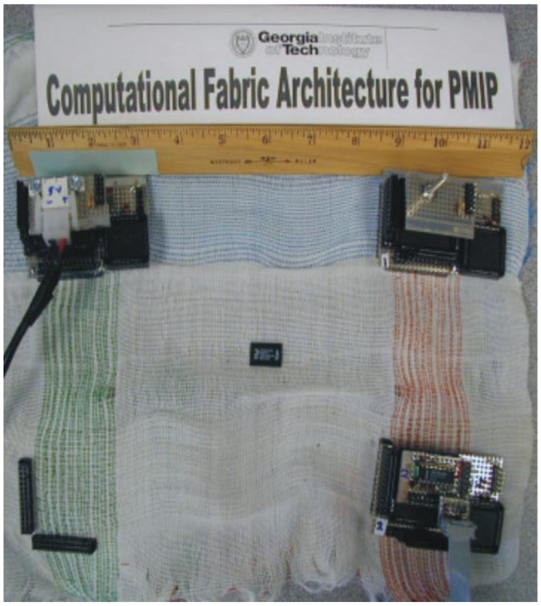

**Figure 4. The PMIP Network in a Fabric**

Two software modules were created; the first was to “demonstrate” the pin-connection discovery algorithm implemented in the system to identify the connections between the various pins on the FPGAs in the fabric and to display the connection paths. This enables discovery of the interconnects on the fly after the manufacturing has been carried out and there is no *a priori* knowledge of the specific connections between the elements in the fabric. The second module discovers the connections and displays the paths on the screen as the discovery process proceeds when the FPGA is powered. To demonstrate the flow of information in the fabric network through the soft interconnects, a potentiometer was attached as a daughterboard to one of the FPGAs and whenever it was “twiddled” (see Figure 4), the resulting change is displayed on the screen (Figures 5 and 6). This recent effort demonstrates the feasibility of realizing a programmable network in a fabric through *soft* interconnects and paves the way for the continued exploration of the “fabric is the computer” paradigm pioneered by the Georgia Tech Wearable Motherboard.

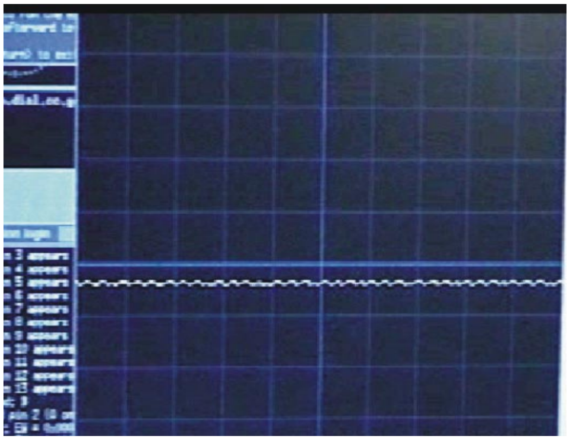

**Figure 5. The Steady State Display**

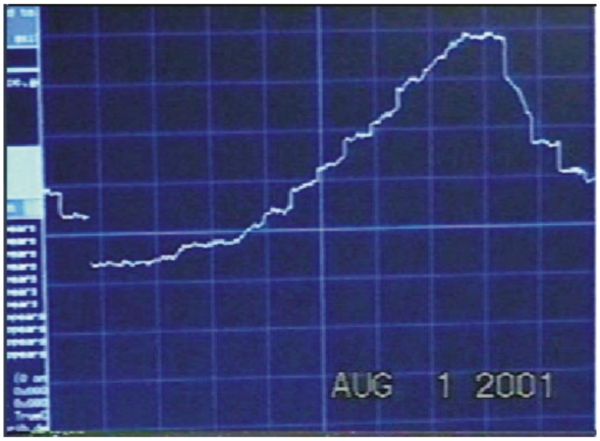

**Figure 6. Flow of Information through the PMIP Fabric.**

## CONCLUDING REMARKS

A well-designed information processing system should facilitate the access of information **A**nytime, **A**nyplace by **A**nyone – the three ***A***s. The ‘ultimate’ information processing system should not only provide for large bandwidths, but also have the ability to see, feel, think, and act. In other words, the system should be totally ‘customizable’ and be in tune with the human. Of course, clothing is probably the only element that is ‘always there’ and in complete harmony with the individual (at least in a civilized society!). And, textiles provide the ultimate flexibility in system design by virtue of the broad range of fibers, yarns, fabrics, and manufacturing techniques that can be deployed to create products for desired end-use applications. A new avenue of research and exploration has opened up for the development of an integrated “textile-computing” system that can serve as a true information processing framework with the ability to sense, feel, think and act based on the end-user stimuli and/or the operational environment. This “fabric is the computer” paradigm exemplified by the Georgia Tech Wearable Motherboard demonstrates the feasibility of realizing personalized mobile information processing (PMIP) and gives new meaning to the term human-machine symbiosis in the context of pervasive/invisible computing.

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