TEXTILES AS A META-WEARABLE:
STUDIES ON TEXTILES AS AN INFORMATION INFRASTRUCTURE

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TEXTILES AS A META-WEARABLE:
STUDIES ON TEXTILES AS AN INFORMATION INFRASTRUCTURE

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With profound gratitude, I dedicate this thesis to

My beloved Parents

&

My loving sister – Sunghee

who have given me endless love and support throughout this journey.

And to

My mentor – Professor Sundaresan Jayaraman

for his inspiration, encouragement, and guidance.

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SUMMARY

Joseph Marie Jacquard (*circa* 1801) created the world's first automatic binary information processor – the Jacquard mechanism. This invention in textile manufacturing was instrumental in bringing about the second Industrial Revolution, also known as the Information Processing Revolution. The significant advancements in sensing, computing and communications technologies have given birth to the paradigm of pervasive information processing. There is a need for convergence of these advanced enabling technologies with textiles to transform the traditionally passive, yet pervasive, textiles into an interactive intelligent information infrastructure for the demanding end-user and facilitate pervasive and personalized mobile information processing.

The primary objective of the research is to design and develop a personal wearable information infrastructure – known initially as the Sensate Liner and then as the Wearable Motherboard – that would be comfortable like any garment and realize the paradigm of "fabric is the computer." Yet another objective is to demonstrate the versatility of the Wearable Motherboard paradigm through applications and develop the concept of textiles as a meta-wearable.

In this dissertation, a structured methodology for product design and development in a concurrent engineering environment has been proposed. A novel technology for creating a full-fashioned woven garment on a loom has been developed, which represents a pioneering contribution to textile engineering. The concept of "interconnections" in a textile structure has been proposed to seamlessly route information from sensors or

devices in any part of the fabric to another through the yarns in the fabric thus creating a flexible textile-based information infrastructure analogous to the traditional printed circuit board (PCB). An interconnection technology has been developed to create interconnects or electrical junctions in textile structures. The concept of Textillography for automating the creation of large-scale interconnects in textile structures has been proposed and defined.

The novel concept of a "Wearable Motherboard" has been proposed. It is a fabric-based information infrastructure, which serves as a flexible and wearable framework into which sensors and devices can be plugged making it similar to a motherboard in an electronic device. This represents true convergence between electronics and textiles giving birth to the field of electronic or "e-textiles."

Real-world instantiations of the Wearable Motherboard – for physiological monitoring (medical, sports, and infants) and in-fabric information processing network – demonstrate the value of the Wearable Motherboard as a platform for personalized mobile information processing and lay the foundation for the next generation of adaptive and responsive textile structures. Fabric-based sensors have been designed and successfully tested to address the shortcomings of gel-based sensors currently used for physiological monitoring. The concept of textiles as a meta-wearable has been realized. It is the bridging catalyst between the Internet of Things (IoT) and the Internet of People (IoP). The vision for the new field of interactive or *i*-textiles has been defined; the advancements realized on the various building blocks during the course of this research have brought this exciting vision closer to reality as seen in the range of commercial products in the marketplace.

CHAPTER 1

Introduction

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 [1]. Yet another invention in the field of textiles – the Jacquard head by Joseph Marie Jacquard (*circa* 1801) – was the first automatic 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 or on the back of the fabric. The 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. Such is the strength of the bond between the fields of textiles and computing.

1.1 Harnessing the Synergistic Relationship

The significant advancements in computing and communications technologies have given birth to the paradigm of pervasive information processing or "information processing on the go." Furthermore, the advancements in, and convergence of, microelectronics, materials, optics and bio technologies, coupled with miniaturization, have led to the development of small, cost-effective intelligent sensors for a wide variety of applications. The transparency of the user interface coupled with the invisibility of the "embedded" technology in the various devices and systems have contributed to the proliferation of these sensors in various applications. By effectively harnessing the benefits of these technological advancements, it is possible to create a system that can provide access to the right information at the right time in the right place, which can indeed make a difference between life and death.

1.1.1 The Principal Dimensions of Textiles (Clothing)

Sensors are pervasive and embedded systems are facilitating information processing *anytime*, *anywhere* for *anyone*. While these types of sensors and networks incorporating such sensors are relatively new in the timeline of civilization, there has been one piece of "sensing" technology since the dawn of civilization. And that is textiles. They were initially (and are still) used for "protection" from the environment – be it from climatic conditions or from other predators as camouflage and personal privacy. This *first* dimension of "protection" has been complemented by the *second* dimension of "aesthetics," exemplified by the success of fashion houses in modern times – from Armani to Zegna.

These two principal dimensions of clothing – protection and aesthetics – have evolved over time; today's clothing is distinctly different (and better) than the first piece of clothing with the development of new fibers, chemicals, and manufacturing technologies, among other advancements. However, clothing has remained "passive." It doesn't "respond" – either automatically or in response to a wearer's actions – to changes in the wearer's environment and/or real-time needs. Thus, clothing is typically associated with the four Ps: It affords Protection from the environment; it conveys Passion; it is Pervasive and it is Passive as shown in Figure 1-1.

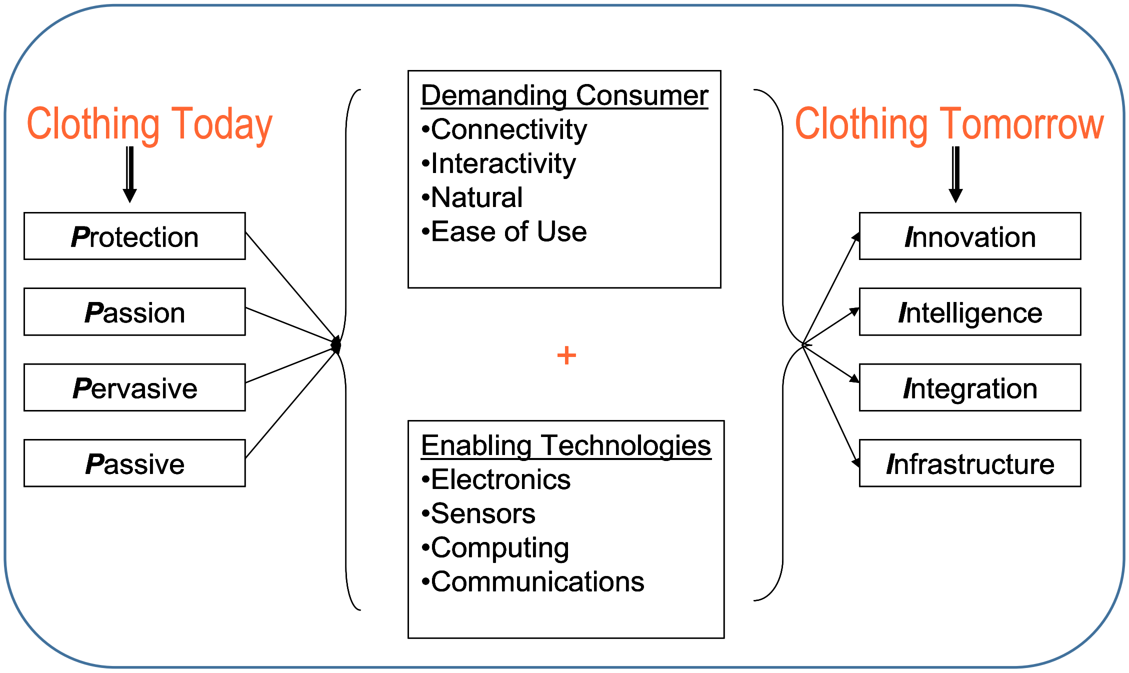


Figure 1-1 Demanding Consumer: The Need for Personalized Mobile Information Processing

1.1.2 Clothing as a Universal Interface

Humans are used to wearing clothes from the day they are born and, in general, no special ‘training’ is required to wear them, i.e., to use the interface. In fact, it is one that can be ‘tailored’ to fit the user’s needs, moods and desires while accommodating the constraints imposed by the ambient environment in which the user interacts with the interface, i.e., different climates, activities and occasions. Moreover, the user doesn't have to spend a lot of time and effort in learning how to use it. The interface can also be fitted to suit the financial resources available to the user. In other words, a garment is probably the most *universal* of interfaces and is one that humans need, use, have familiarity with, enjoy, and which can be easily customized. This “universal interface” of clothing is in contrast to typical computer interfaces/systems (e.g., Unix®, Windows®, Linux®, iOS®, Android®) each of which has unique characteristics and requires time and effort to learn to use.

1.1.3 Meeting the User’s Demands: Need for Convergence

Today’s individual is extremely active – or dynamic – and is demanding. The explosion of technology – information, electronics, sensors and communications – has fueled this demanding nature of the individual seeking total “interactivity” with surrounding objects and the environment (see Figure 1-1). In fact, the individual (e.g., soldier) becomes an information node or sensor gathering valuable ambient intelligence or situational awareness from the battlefield and transmitting it to the command and control center where that information is transformed into knowledge so that the mission, and hence the soldier, are safe and successful. So, the ultimate information processing system for this demanding user should not only provide for large bandwidths, but also have the ability to sense, feel, think, and act. In other words, the system should be personalized – totally customizable and be “in-sync” with the human.

1.1.4 Enhancing the Quality of Life: Need for Convergence

There is yet another facet that is dramatically affecting the quality of life for individuals, viz., the lack of access to affordable and high-quality healthcare. According to an Institute of Medicine (now, the National Academy of Medicine) report, “The uninsured have poorer health and shortened lives [2]. In another study, the Institute of Medicine concluded “The U.S. healthcare delivery system does not provide consistent, high-quality medical care to all people” [3]. The long-term implications of lack of quality healthcare on society are significant: The economic vitality of a nation is limited by the poorer health, premature death and long-term disability of individuals without proper access to healthcare.

Patients discharged after major surgeries (e.g., heart bypass) typically experience a loss of sense of security when they leave the hospital because they feel "cut off" from the continuous watch and care they received in the hospital. This degree of uncertainty can greatly influence their post-operative recovery. Therefore, there is a need to continuously monitor such patients (at home) and give them the added peace of mind so that the positive psychological impact will speed up the recovery process. Mentally ill patients (e.g., those suffering from manic depression) need to be monitored on a regular basis to gain a better understanding of the relationship between their physical condition (e.g., vital signs) and their behavioral patterns so that their treatments (e.g., medication) can be suitably modified. Such medical monitoring of individuals is critical for the successful practice of telemedicine that is becoming economically viable in the context of advancements in computing and telecommunications. Likewise, continuous monitoring of astronauts in space, of athletes during practice sessions and in competition, and of law enforcement personnel in the line of duty are all extremely important. Therefore, there is a need for an effective and mobile information infrastructure or monitoring system that can be tailored to the individual's requirements and thereby enhance the quality of life.

1.1.5 Textiles: The Convergence Platform and the Third Dimension of Intelligence

There is a need for convergence of the enabling technologies of electronics, sensors, computing and communications with textiles so that the traditionally passive, yet pervasive, textiles can be transformed into an interactive, intelligent information infrastructure for the demanding end-user to facilitate pervasive and personalized mobile information processing as shown in Figure 1-1. Since clothing is pervasive and presents a universal interface, it has the potential to meet the emerging needs of today’s dynamic individual while enhancing the quality of life for humans. It can provide interactivity, connectivity, ease of use and a natural interface for information processing as shown in the figure.

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. Moreover, fabrics provide large surface areas that may be needed for hosting the large numbers of sensors and processors that might be needed for both today’s demanding consumer, a sick patient, or for deployment over large terrains, e.g., a battlefield. The opportunities to build in redundancies for fault tolerance make textiles an ideal platform for information processing.

Textiles can therefore serve as a true information-processing infrastructure with the ability to *sense*, *feel*, *think* and *act* based on the wearer's stimuli and/or the operational environment in which the textiles are deployed. The technology enablers – sensors, processors and devices – can be effectively integrated into traditional textiles to add the third dimension of intelligence to textiles resulting in the next generation of "Interactive Textiles" or i-Textiles, and pave the way for the paradigm of "fabric is the computer" – the ultimate integration of textiles and information processing or computing. Figure 1-2 is a conceptual representation of this integration between an exquisite textile fabric and a network of sensors and processors leading to an innovative, intelligent information infrastructure that is customizable, has the typical look and feel of traditional textiles, and can meet the demands of today's dynamic individual.

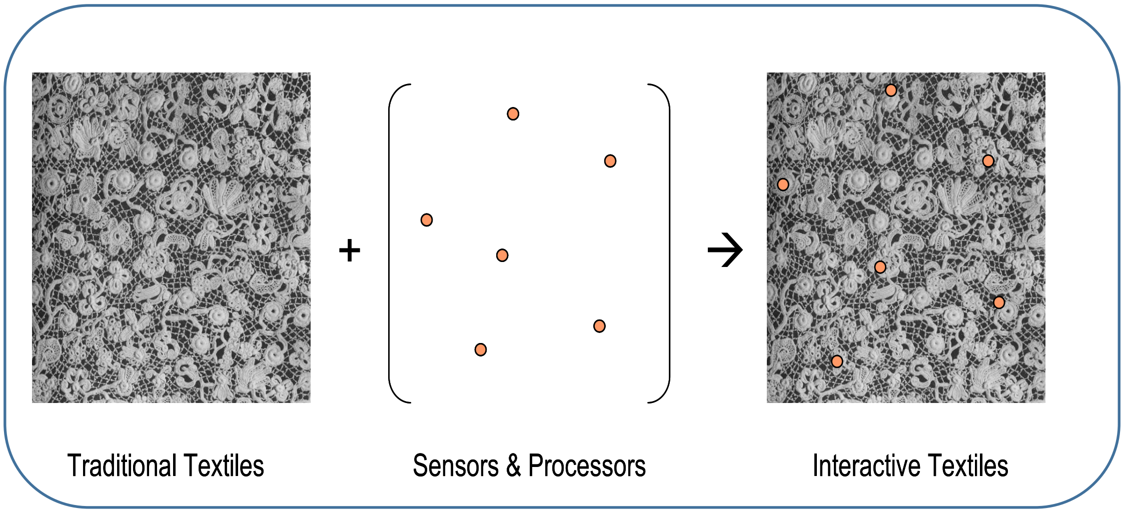


Figure 1-2 Integration of Sensors and Processors into Exquisite Traditional Textiles

1.1.6 Innovation: The Lifeblood of the Textile/Apparel Complex

Today, the textile/apparel industry is undergoing a dynamic transformation around the world. Globalization, customization and value are the dominant themes. Companies are attempting to become flexible, agile and responsive to meet these rapidly changing demands from increasingly value-conscious consumers around the world by adopting information technology and effective supply chain management techniques [4]. However, the industry can thrive only when it reinvents itself by pioneering new paradigms in textiles and clothing. Innovation will be ever so critical to the success of the textile/apparel complex in the 21st Century. The paradigm of i-Textiles provides a valuable avenue for the resurgence of the US textile/apparel industry, which has seen manufacturing being lost to low-wage countries during the past three decades.

1.2 Motivation for the Research

It is hard to place a price on human life. Unfortunately, casualties are associated with combat and sometimes are inevitable. The loss of even a single soldier in a war can alter the nation's engagement strategy making it all the more important to save lives. The limited medical resources on the battlefield must be harnessed optimally to minimize casualties by identifying and attending to injured soldiers during the "Golden Hour." Therefore, the value of any effort to minimize loss of human life is priceless.

The motivation for this research to create a wearable sensor network in a textile infrastructure came from the need to enhance the quality of life for soldiers by harnessing the ambient intelligence in the battlefield. Since medical resources are limited in a combat zone, a technology that could – in real-time – determine the condition of the wounded soldier would help the medic save valuable time in attending to the soldiers within the Golden Hour. The twin requirements for this smart triage are to identify where the soldier has been shot and what his vital signs (e.g., heart rate, temperature) are. The ideal infrastructure available to create this sensor network was determined to be the soldier's uniform because the clothes are in continuous contact with the soldier's body, which is the source of signals for the various vital signs characterizing the soldier's physical condition.

Moreover, the functionality, modularity, flexibility (plug and play) required of the fabric-based sensor network led to exploring the concept of the motherboard paradigm. Just as special purpose chips and processors can be plugged into a computer motherboard to obtain the desired information processing capability (e.g., high-end graphics), the motherboard paradigm provides a versatile framework for the incorporation of sensing, monitoring and information processing devices. The significant difference is that the proposed motherboard would be "wearable" like a piece of clothing with the desired look and feel, thus leading to the new paradigm of the "Wearable Motherboard."

1.3 Research Objectives

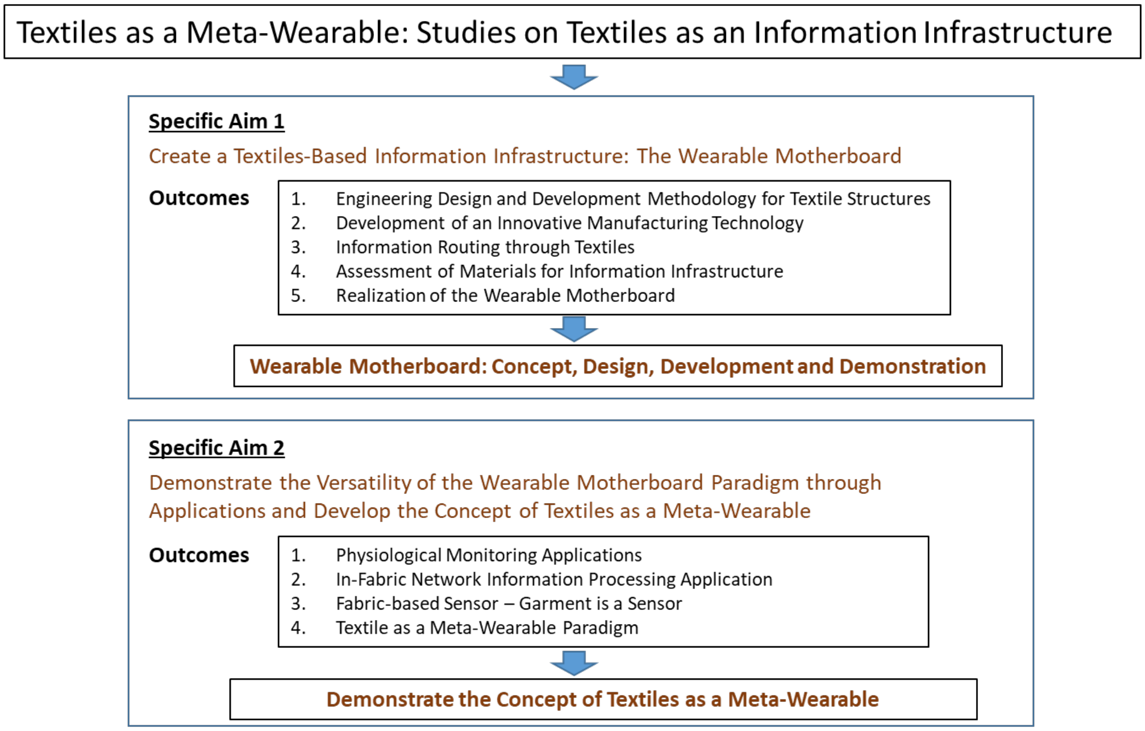
The primary objective of the research has been to design and develop a personal wearable information infrastructure – known initially as the Sensate Liner and then as the Wearable Motherboard – that would be comfortable like any garment and realize the paradigm of "fabric is the computer." Yet another objective is to demonstrate the versatility of the Wearable Motherboard paradigm through applications and develop the concept of textiles as a meta-wearable: An information infrastructure or platform that will be unobtrusive, natural, pervasive, and afford multifunctional capabilities. In addition to serving as a wearable in its own right, the platform is designed to *host* or hold other "wearables" or sensors in place and provide *data buses* or pathways to carry the signals (and power) between sensors and the information processing components in the sensor network.

1.3.1 The Research Framework

Figure 1-3 shows the objectives and the overall framework for the research. The two Specific Aims are as follows:

1. Create a textile-based information infrastructure: The Wearable Motherboard; and
2. Demonstrate the versatility of the Wearable Motherboard paradigm through applications and develop the concept of textiles as a meta-wearable.

For each Specific Aim, the corresponding expected outcomes from the research are shown in the figure. By realizing these outcomes, the overall objective of the research will be accomplished.



Textiles as a Meta-Wearable: Studies on Textiles as an Information Infrastructure

Specific Aim 1

Create a Textiles-Based Information Infrastructure: The Wearable Motherboard

Outcomes

1. Engineering Design and Development Methodology for Textile Structures
2. Development of an Innovative Manufacturing Technology
3. Information Routing through Textiles
4. Assessment of Materials for Information Infrastructure
5. Realization of the Wearable Motherboard

Wearable Motherboard: Concept, Design, Development and Demonstration

Specific Aim 2

Demonstrate the Versatility of the Wearable Motherboard Paradigm through Applications and Develop the Concept of Textiles as a Meta-Wearable

Outcomes

1. Physiological Monitoring Applications
2. In-Fabric Network Information Processing Application
3. Fabric-based Sensor – Garment is a Sensor
4. Textile as a Meta-Wearable Paradigm

Demonstrate the Concept of Textiles as a Meta-Wearable

Figure 1-3 The Research Framework: Specific Aims and Outcomes

1.4 Concurrent Developments in the Field

The research presented in this dissertation began in 1996 and laid the foundational building blocks for the field of smart or electronic textiles. The Smart Shirt developed in this research has been recognized as being the "first documented idea for an intelligent shirt" and "ahead of its time" [5]. Since then, extensive research has been carried out as seen in the number of books, special issues of journals, and presentations at major conferences such as the IEEE EMBS Annual Conferences, establishment of the IEEE Technical Committee on Smart Textile-based Wearable Biomedical Systems and development of standards by organizations, such as IPC [6, 7, 8]. The European Commission (EC) has been a major source of funding research in this area through its suite of projects [9, 10, 11, 12, 13]. These projects followed two complementary approaches: the "application pull” approach (supported by the “eHealth” sector) and the “technology push” approach (supported by the “micro and nanosystems” sector) [14]. Major prototype systems and applications include:

- Continuous measurement and control of glucose concentration in subjects with Type 1 diabetes, enabling the provision of better adjustment of insulin dosage [10];
- Personal ECG monitoring [11] for early detection and management of cardiac events, including recording, storage, and synthesis of standard 12-lead ECGs, self-adaptive data processing, decision support, and alarm generation;
- A wrist multi-sensor device for continuous monitoring of health status and alert, integrating biomedical sensors for heart rate, 1-lead ECG, blood pressure, oxygen blood saturation, and skin temperature measurement [12]; and
- A personal mobile health service platform for vital signs monitoring based on a body area network, utilizing the next generation of public wireless networks [13].

In the area of intelligent biomedical clothing, the EC has funded projects that have led to the following key developments [14, 15]:

- VTAMN is a T-shirt made from textile with woven wires, incorporating four smooth, dry ECG electrodes; a breath rate sensor; a shock/fall detector; and two temperature sensors [16];
- WEALTHY is a wireless-enabled garment with embedded textile sensors for simultaneous acquisition and continuous monitoring of biomedical signs like ECG, respiration, EMG, and physical activity [17]. The “smart cloth” embeds a

strain fabric sensor based on piezo-resistive yarns and fabric electrodes realized with metal-based yarns; and

- MagIC is a sensor vest including fully woven textile sensors for ECG and respiratory frequency detection and a portable electronic board for motion assessment, signal preprocessing, and bluetooth connection for data transmission [18].

In addition to the aforementioned projects, research is being carried out in academic institutions and companies around the world in the area of smart textiles. The most recent of these is the Advanced Functional Fabrics of America, one of the National Network of Manufacturing Innovation (NNMI) Institutes, established in 2016 by the US Department of Defense [19].

1.4.1 Smart Textiles through Printed Electronics

Printed electronics is another technology developed for creating smart textiles. The first of these, known as PrinTronix®, represents the convergence of textiles, conductive materials, printing technology and information technology to create fabric-based intelligent flexible electronics [20]. PrinTronix transforms the traditional paradigm of “printing for design” to “printing for functionality.” The embedded conductive electrical circuits can then be utilized for a variety of applications including heating, signal transmission, information processing, and smart sensing with integrated sensors and connectors.

HeaTex® is a heating textile and represents the commercial realization of PrinTronix technology. HeaTex is composed of several layers of different ranges of electrically conductive materials as shown in Figure 1-4. The power for the printed circuit comes from a 7.4V rechargeable lithium-polymer battery. The user can regulate the warmth using the controller with three different temperature settings in the range 35ºC to 45ºC and be comfortable. As seen in the figure, the heat distribution is uniform across the fabric surface at the three temperatures. Additionally, the temperature can be controlled remotely using the wireless HeaTex® Temperature Controller also shown in the figure.

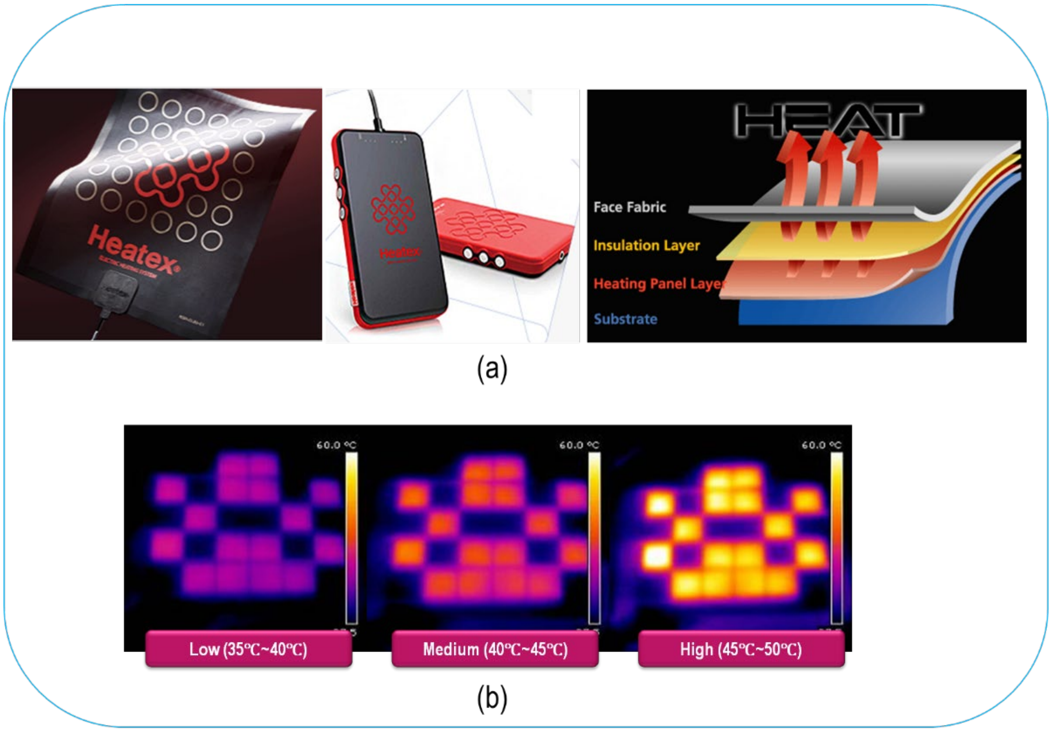


Figure 1-4. Heatex: Fabric-based Printed Electronics Heating System [21]

(a) Heatex, Temperature Controller and Structure
(b) Uniform Heat Distribution at Different Temperature Settings

The configuration of the HeaTex fabric – size, shape and heating temperature range – can be customized to suit the application; since it does not add any appreciable weight or volume to a typical fabric, the intrinsic properties of the base materials used for the clothing are not altered as seen in the jacket in Figure 1-5. HeaTex can be washed in a typical washing machine without loss of performance. Additionally, studies have shown that the blood flow of the wearer improves due to the far infrared emission from the heating elements in HeaTex [21]; it also provides anti-bacterial properties with a bacteriostatic reduction rate of 99.9%. These additional capabilities further contribute to enhancing the user's comfort, especially for the soldier on the battlefield.

Figure 1-5. The HeaTex Jacket [21]

1.4.2 The Smart Textiles Market

During the course of this research, several products have been introduced in the market. The market for smart textiles was valued at $93.3 Billion in 2018 and has been projected to reach $475.62 Billion by 2025 with the CAGR of 31.25% between 2019 and 2025 [22]. According to this latest smart textiles market analysis report, the driving force for the industry is the expected increase in adoption in sports and fitness, and in the military. The high cost of production is viewed as a restraining factor in the growth of the industry.

Examples of commercial products include the Smart Bra Heart Rate Monitor from Adidas [23], Athos Training System from MAD Apparel [24], Smart Socks from Sensoria Fitness [25], PoloTech Smart Shirt from Ralph Lauren [26], and Zephyr

Performance Systems from Medtronic [27], to name a few. These commercial products shown in Figure 1-6 illustrate the viability of the fundamental concepts developed during the course of the research presented in this dissertation.

Zephyr Athos Athos

Adidas Ralph Lauren Sensoria

* Images: From respective companies listed with the images

Figure 1-6. Smart Textile Products in the Market

1.5 Organization of the Dissertation

The remainder of the dissertation is organized along the Specific Aims and Outcomes in Figure 1-3. Chapters 2 through 6 discuss the research leading to the corresponding outcomes for Specific Aim 1. Chapter 7 and 8 discuss the research leading to the corresponding outcomes for Specific Aim 2. Conclusions and recommendations for future research are presented in Chapter 9.

CHAPTER 2

Textile-Based Information Infrastructure: Design and Development Methodology

In this Chapter, we discuss the complex nature of the design of textile structures. We present the two major performance requirements of the Sensate Liner for monitoring the conditions of soldiers in battlefield. We develop a structured methodology for the design of the Sensate Liner, a textile-based information infrastructure.

2.1 Engineering Design of Textile Structures

The engineering design of textile structures is a complex task. The task is made even more complex because of the significant interactions between the different design parameters that ultimately determine the properties of a textile structure. To illustrate this, consider Table 2-1 that depicts the interrelationships between major design parameters and functional characteristics of woven structures [28]. The variables in the first column (e.g., fiber linear density, yarn count, thread spacing, etc.) have a significant influence on the resulting functional properties of the fabric (e.g., tensile strength, air permeability, flexural rigidity, etc.) shown in the other columns. Thus, if we try to increase the fabric tensile strength by increasing the thread density, it will make the fabric stiffer and reduce air-permeability. Thus, engineering the desired end use properties into textile structures requires many trade-offs and becomes more complicated if the design has to accommodate additional constraints imposed by fabrication technologies, marketing, etc.

Table 2-1 Engineering Design of Woven Structures [28]

Increase Only	Tensile Strength	Initial Modulus	Tearing Strength	Bending Stiffness	Air-Permeability	Abrasion Resistance	Shear Resistance	Flexural Endurance	Thickness
Fiber Linear Density (Cross-Sectional Area)	—	—	—	↑	↑	↑	—	↓	↑
Yarn Linear Density	↑	↑	↑	↑	↓	↑	↑	⤵	↑
Yarn Twist	⤵	↓	—	↑	↑	⤵	↑	⤵	⤵
Threads / inch	⤵	↑	↓	↑	↓	↑	↑	↓	↑
Interlacings / unit area (Weave Pattern)	↓	↓	↓	↑	↓	↑	↑	↓	↑

Traditionally, the various operations in the fabric or apparel industry, such as design, engineering, manufacturing and marketing are carried out sequentially and as separate functions. This leads to conflicting goals for the various functions and the strategic intent of the enterprise is lost. To avoid this problem, enterprises are increasingly using cross-functional teams and techniques such as Quality Function Deployment (QFD), Design for Manufacturing (DFM), Total Quality Management (TQM), etc. As a result, the time from concept to market is typically reduced [29]. This technique of integrating all the steps in the product life cycle -- from design conceptualization to marketing -- during the product design process is referred to as concurrent engineering or integrated product/process development (IP/PD).

2.2 Quality Function Deployment

The concept of Quality Function Deployment (QFD) was introduced in Japan by Yoji Akao in 1966 [30]. According to Akao [31], QFD “is a method for developing a design aimed at satisfying the consumer and then translating the consumer's demand into design targets and major quality assurance points to be used throughout the production phase. QFD is a way to assure design quality while the product is still in the design stage”. Akao has pointed out that, when appropriately applied, QFD has demonstrated the reduction of development time by one-half to one-third. According to Sullivan [32], “The main objective of any manufacturing company is to bring out new products to market sooner than the competition with lower cost and improved quality. One mechanism to do this is Quality Function Deployment, which provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales). In QFD, all operations are driven by the 'voice of the customer'; QFD therefore represents a change from manufacturing-process quality control to product-development quality control". Sullivan further notes that, "The QFD system has been used by Toyota since 1977, following four years of training and preparation. Results have been impressive. Between January 1977 and April 1984, Toyota introduced four new van-type vehicles. Using 1977 as a base, Toyota reported a 20% reduction in start-up costs on the launch of the new van in October 1979; a 38% reduction in November 1982; and a cumulative 61% reduction in April 1984. During this period, the product development cycle (time to market) was reduced by one-third with a corresponding improvement in quality because of a reduction in the number of engineering changes". Dean [33] views QFD as a system engineering process that transforms the desires of the customer/user into the language required by the design process. It also provides the glue necessary, at all project levels, to tie all components together and to manage them. It is an excellent method to ensure the customer obtains a high value from the product, actually the intended purpose of QFD.

At its core, QFD is a structured process that uses a visual language and a set of inter-linked engineering and management charts to transform customer requirements into design, production, and manufacturing process characteristics. The result is a systems engineering process that prioritizes and links the product development process to the design so that it assures product quality as defined by the customer. Additional power is derived when QFD is used within a concurrent engineering environment. Jayaraman has discussed the importance of concurrent engineering for product development in the textile-apparel complex and identified the key information-related issues associated with the practice of concurrent engineering [34, 35].

We now discuss the methodology for the design and development of the sensate liner using the QFD methodology.

2.3 Design Conceptualization: Detailed Analysis of the Key Performance Requirements

The two key performance requirements of the Sensate Liner for Combat Casualty Care are to:

- Detect the penetration of a projectile (e.g., bullets and shrapnel); and
- Monitor the soldier's vital signs.

The vital signs would be transmitted to the triage unit by interfacing the Sensate Liner with a Personal Status Monitor (PSM) developed by the US Defense Advanced Projects Research Agency (DARPA) [36].

The first step in the QFD process is to identify the various characteristics required by the customer in the product being designed. Therefore, using the information obtained [36, 37] from the US Navy (the "customer") on the two key performance requirements for the proposed Sensate Liner, an extensive analysis has been carried out. A detailed specific set of performance requirements has been defined; the result is shown in Figure 2-1. These are Functionality, Usability in Combat, Wearability, Durability, Manufacturability, Maintainability, Connectability and Affordability. The next step has been to examine these requirements in-depth and to identify the key factors associated with each of them. These are also shown in the figure. For example, Functionality implies the Sensate Liner must be able to detect the penetration of a projectile and should also monitor body vital signs -- the two performance requirements.

The factors deemed critical in battlefield conditions are shown under Usability in Combat in the figure. These include providing physiological thermal protection, resistance to petroleum products and EMI (electromagnetic interference), minimizing signature detectability (thermal, acoustic, radar and visual), offering hazard protection while facilitating electrostatic charge decay and being flame-and directed-energy retardant.

Likewise, as shown in the figure, Wearability implies that the Sensate Liner should be lightweight, breathable, comfortable, easy to wear and take-off, and provide easy access to wounds – critical requirements in combat conditions so that the soldier's performance is not hampered by the protective garment. Durability of the Sensate Liner is another important performance requirement; it should have a wear life of 120 combat days and should withstand repeated flexure and abrasion – both of which are characteristic of combat conditions. Manufacturability is another key requirement since the design (garment) should eventually be produced in large quantities over the size range for the soldiers; moreover, it should be compatible with standard issue clothing and equipment. Maintainability of the Sensate Liner is an important requirement for the hygiene of the soldiers in combat conditions; it should withstand field laundering, should dry easily and be easily repairable (for minor damages). The developed Sensate Liner should be easily connectable to sensors and the Personal Status Monitor (PSM) on the soldier. Finally, affordability of the proposed Sensate Liner is another major requirement so that the garment can be made widely available to all combat soldiers to ensure their security, and hence that of the nation.

Thus, in the first step of the design conceptualization process, the broad performance requirements has been translated into a larger set of clearly defined requirements along with the associated factors (Figure 2-1).

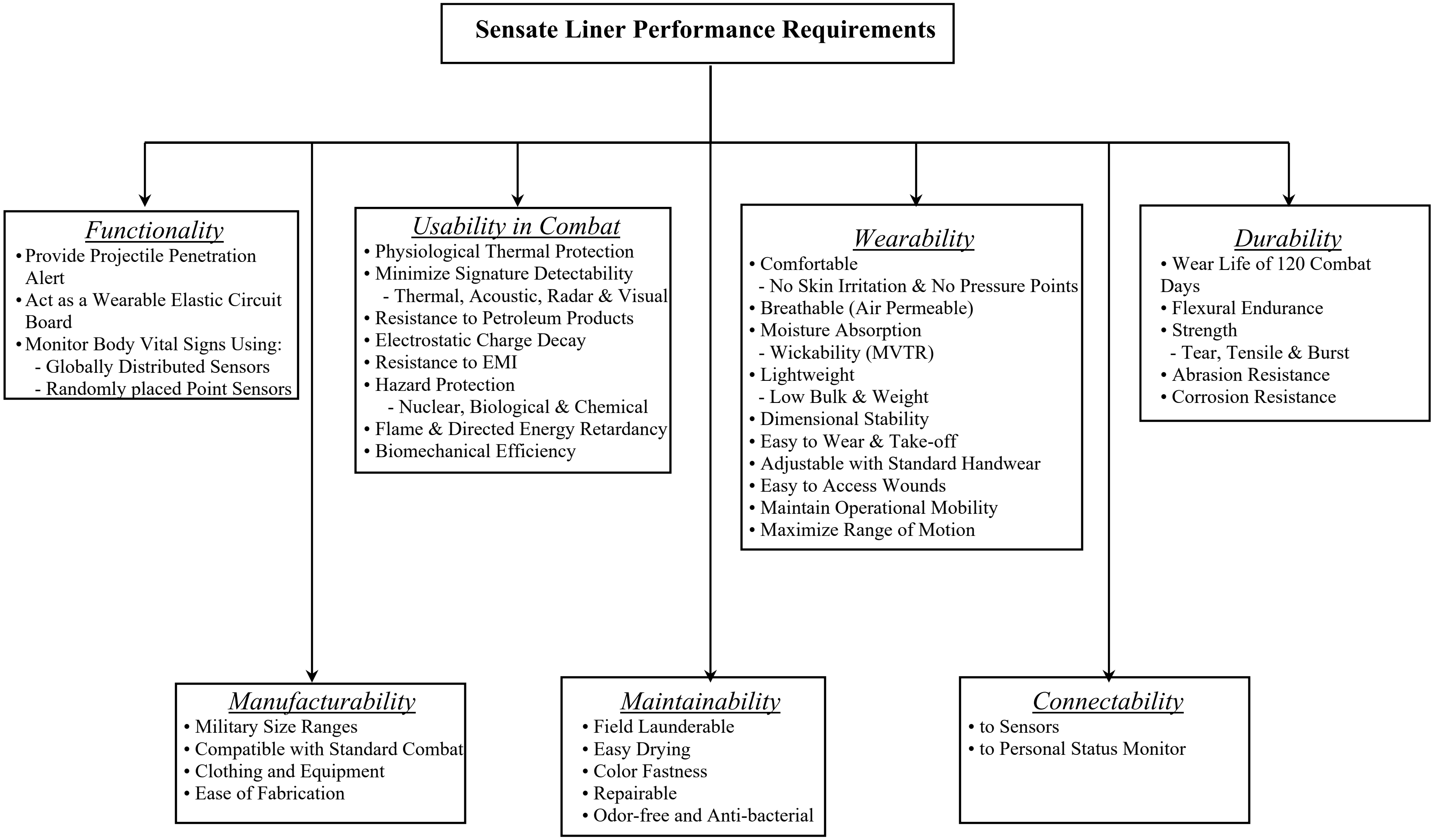


Figure 2-1 Sensate Liner for Combat Casualty Care: Performance Requirements

2.4 The Sensate Liner Design and Development Framework

Once the detailed performance requirements were defined, the need for an overall design and development framework became obvious. Since no comprehensive framework was found in literature, research has been carried out to develop one. Figure 2-2 shows the resulting overall Sensate Liner Design and Development Framework; it encapsulates the modified QFD-type methodology developed for achieving the project goals. As shown at the top of the figure, the first step has been to identify the key performance requirements for the Sensate Liner (details shown in Figure 2-1). These **Requirements** are then translated into appropriate **Properties** of Sensate Liner: sets of Sensing and Comfort properties. The **Properties** lead to the specific **Design** for the Sensate Liner: dual structure meeting the twin requirements of “sensing” and “comfort.” These **Properties** in the **Design** are achieved through the appropriate choice of **Materials & Fabrication Technologies** by applying the corresponding **Design Parameters** as shown in the figure. These major facets in the proposed framework are linked together as shown by the arrows between the dotted boxes in Figure 2-2. This overall comprehensive design and development framework is now analyzed in greater detail.

The next step in the design process is to translate the performance requirements (in Figure 2-1) into specific properties that must be engineered into the Sensate Liner leading to its design. The results of this step are shown in the second dotted box in the framework in Figure 2-2.

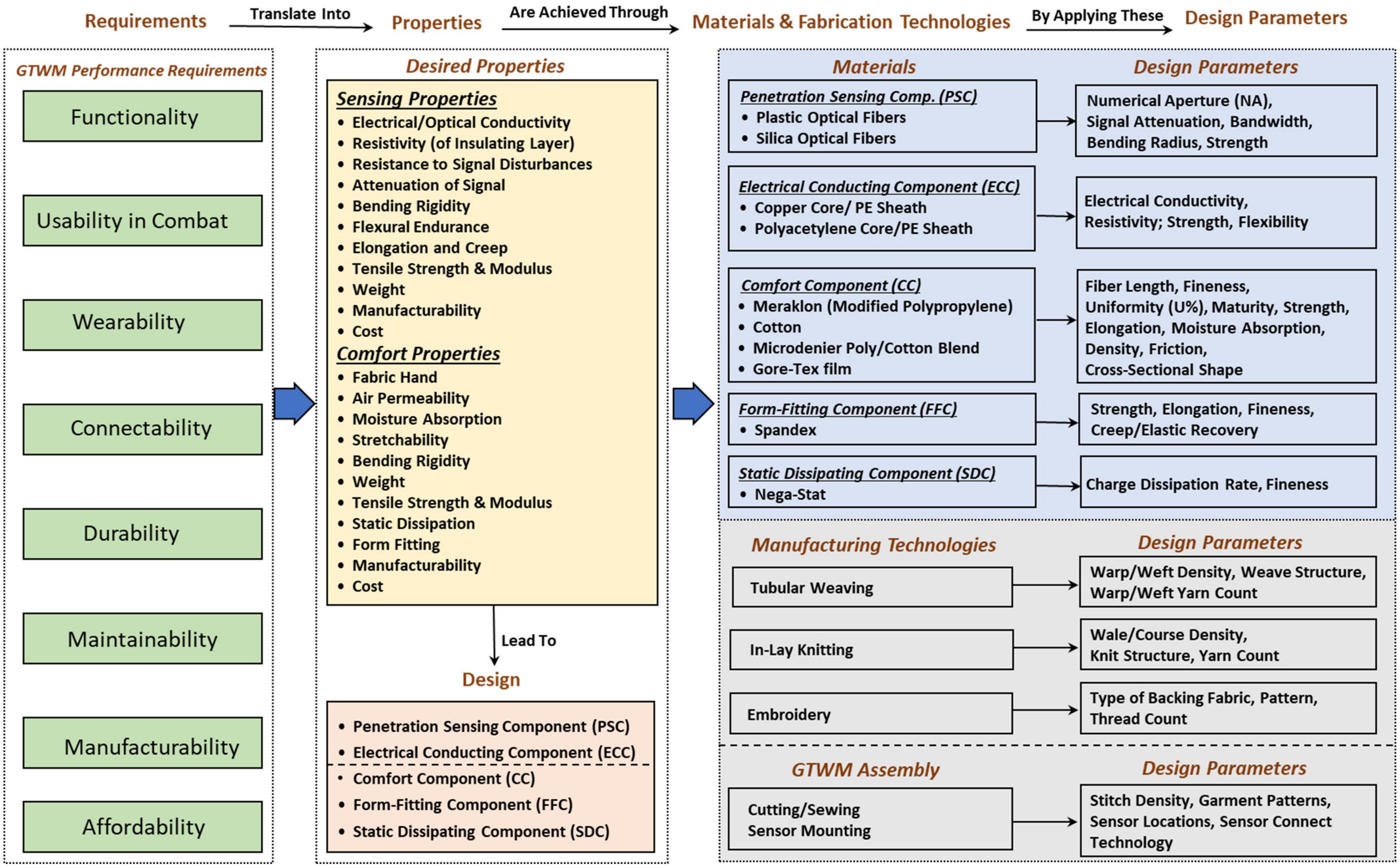


Figure 2-2 Sensate Liner Design and Development Framework

2.4.1 Sensate Liner Design: Desired Set of Properties

As seen in the figure 2-2, the desired properties have been divided into Sensing and Comfort characteristics. For example, the Sensing properties include electrical/optical conductivity, resistance to signal disturbances, minimum signal attenuation due to deformation during manufacturing and/or use, and low weight. The key Comfort properties include fabric hand (e.g., how soft the fabric/garment feels to touch), air permeability and moisture absorption to ensure a breathable and comfortable garment, static dissipation, stretchability to ensure a form-fitting garment, etc. Bending rigidity, flexural endurance, weight and tensile properties are the common set of properties that are derived from other performance requirements in Figure 2-1. Manufacturability and cost are the two underlying parameters of the proposed design.

2.4.2 Sensate Liner: The Proposed Design and Structure

Based on a critical analysis of the sets of Sensing and Comfort properties required of the Sensate Liner, the next step has been to propose a design to achieve the desired properties in the most cost-effective manner while ensuring its manufacturability. Sensate Liner will be an integrated structure comprising the major components shown at the bottom of the second dotted box (**Design**) in the framework in Figure 2-2:

- <u>Penetration Sensing Component (PSC):</u> will pinpoint the location of projectile penetration and will be linked to the Personal Status Monitor (PSM) through the connectors at the hip level;

- Electrical Conducing Component (ECC): will monitor body vital signs including heart rate, temperature and blood pressure through sensors on the body and transmit to the PSM positioned at the soldier's hip level;
- Comfort Component (CC): will be in immediate contact with the soldier's skin and will provide the necessary comfort properties for the garment (similar to the regular issue undershirt);
- Form-Fitting Component (FFC): will provide the necessary form-fit to the soldier; more importantly, it will keep the sensors in place on the soldier's body during combat conditions;
- Static Dissipating Component (SDC): will quickly dissipate any built-up static charge during usage.

Since the penetration sensing component and electrical conducting component are carrying "information," they are collectively referred to as the information infrastructure component.

2.4.3 Realizing the Sensate Liner Design: Materials and Fabrication Technologies

As shown in the framework in Figure 2-2, the next step has been to identify the materials and fabrication technologies that can be utilized to achieve the proposed design of the Sensate Liner with the desired properties. The results of the steps are shown in the third dotted box in the figure. The design parameters associated with the materials and fabrication technologies (shown at the far end of the third dotted box) denote the corresponding variables that can be modified to achieve the desired properties and performance in the Sensate Liner.

2.4.4 Materials Evaluation and Selection

The Sensate Liner Performance Requirements and Properties in Figures 2-1 and 2-2 has been used to develop the criteria for evaluating the materials for the various components of the Sensate Liner. Based on these criteria, several materials have been evaluated for each Sensate Liner component using a weighted prioritization matrix approach [38]. The resulting matrix has been used to identify the candidate materials for various components of the Sensate Liner. The candidate choices and corresponding design parameters are shown in the third dotted box in Figure 2-2. This structured approach to the evaluation of multiple alternatives during product design ensures that the right choice is made.

2.4.4.1 Materials for Penetration Sensing Component (PSC)

Penetration alert can be achieved by the use of either an electrically conductive mesh or an optical fiber mesh. The response time of an electrical mesh has been shown to be too slow to 'catch a bullet' [37]. Second, conductive fibers are susceptible to electromagnetic interference and have to be shielded to prevent shorting when wet. On the other hand, optical fibers do not suffer from these limitations. Based on these relative merits, optical fibers have been chosen over conductive fibers for the PSC.

For sensing the penetration of the projectile, the choice has been narrowed down to silica-based optical fibers and plastic optical fibers [39, 40]. The design evaluation matrix shown in Table 2-2 provides a comparative evaluation of the two candidate materials for the PSC. The evaluation criteria in the first column have been derived from the performance requirements (Figure 2-1) and properties of the PSC (Figure 2-2).

Table 2-2 Design Evaluation Matrix for Penetration Sensing Component (PSC)

Weights: %; Score: Scale of 0 (worst) to 4 (best)

Property (Evaluation Criterion)	Weight (%)	Silica Optical Fiber	Plastic Optical Fiber
Optical Conductivity	20	4	4
Resistance to Electromagnetic Interference	15	4	4
Attenuation of Signal	15	3	3
Bending Rigidity/Flexural Endurance	15	1	3
Manufacturability	10	1	3
Elongation and Creep Recovery	7.5	2	3
Weight	7.5	2	4
Tensile Strength and Modulus	5	2	3
Availability	2.5	4	4
Cost	2.5	2	2
Total Score	**100**	**2.7**	**3.4**

The relative weights of these evaluation criteria are listed in the second column in the table. The weight denotes the importance of the specific criterion towards the performance of the Sensate Liner. For example, optical conductivity has the greatest impact on the performance of the PSC (and hence the Sensate Liner), and is therefore assigned the highest weight (20%). This is followed by resistance to electromagnetic interference (15%), attenuation of signal (15%), and so on. For each evaluation criterion, a score has been assigned to the material based on its ability to meet that criterion (0-poor to 4-best). For example, the bending rigidity/flexural endurance of silica-based optical fiber is considerably poor when compared to that of plastic optical fiber. Therefore, the former is assigned 1 while the latter is assigned 3 in the table. Based on the individual weights and corresponding scores, a weighted score ($\sum weight_i * score_i$) has been computed for each material choice and is shown in the last line of the table. The higher the final weighted score, the greater the probability that the material will successfully meet all the evaluation criteria and hence higher the chance of producing an effective Sensate Liner for combat conditions. Based on the prioritization matrix in Table 2-2, POF has been chosen for the PSC in the Sensate Liner.

2.4.4.2 Materials for Electrical Conducting Component (ECC)

The ECC will monitor body vital signs including heart rate, temperature and blood pressure through sensors on the body and will be transmitted to the PSM positioned at the soldier's hip level. The choice of materials includes the three classes of intrinsically conducting polymers, doped inorganic fibers and metallic fibers, respectively. A comparative analysis of these materials has been carried out.

Intrinsically Conducting Polymers: Polymers that conduct electric currents without the addition of conductive (inorganic) substances are known as "intrinsically conductive polymers" (ICP) [41, 42]. Electrically conducting polymers have a conjugated structure, i.e., alternating single and double bonds between the carbon atoms of the main chain [43]. In the late 1970s, it was discovered that polyacetylene could be prepared in a form with a high electrical conductivity, and that the conductivity could be further increased by chemical oxidation. Thereafter, many other polymers with a conjugated (alternating single and double bonds) carbon main chain have shown the same behavior, e.g., polythiophene and polypyrrole. In the beginning, it was believed that the processability of traditional polymers and the discovered electrical conductivity could be combined. However, it has been found that the conductive polymers are rather unstable in air, have poor mechanical properties and cannot be easily processed [43]. Also, all intrinsically conductive polymers are insoluble in any solvent and they possess no melting point or other softening behavior. Consequently, they cannot be processed in the same way as normal thermoplastic polymers and are usually processed using a variety of dispersion methods [44]. Because of these shortcomings, fibers made up of fully conducting polymers have not been considered for use in the Sensate Liner.

Since fibers made up of intrinsically conducting polymers are rather unstable, they are often doped or coated on the surface of regular polymeric fibers such as polyester and nylon. However, these fibers do not have high conductivity and are usually used for static dissipation in fabrics [41]. The conductivity of the coated fibers decreases considerably when they are repeatedly laundered and this is a disadvantage since the Sensate Liner must be laundered (see Figure 2-1).

Inorganic Conducting Fibers: Yet another class of conducting fibers consists of those that are doped with inorganic or metallic particles. The conductivity of these fibers is quite high if they are sufficiently doped with metal particles, but this would make the fibers less flexible. Such fibers can be used to carry information from the sensors to the monitoring unit if they are properly insulated [41, 42].

Metallic Fibers: Metallic fibers such as copper and stainless steel insulated with polyethylene or polyvinyl chloride may be one of the best choices for the conducting fibers in the Sensate Liner. With their exceptional current carrying capacity, copper and stainless steel are more efficient than any doped polymeric fibers. Also, metallic fibers are strong and they resist stretching, neck-down, creep, nicks and breaks very well.

Therefore, metallic fibers of very small diameter (of the order of 0.1 mm) will be sufficient to carry information from the sensors to the monitoring unit. Even with insulation, the fiber diameter will be less than 0.3 mm and hence these fibers will be very flexible and can be easily incorporated into the Sensate Liner. Also, the installation and connection of metallic fibers to the PSM unit will be simple and there will be no need for special connectors, tools, compounds and procedures.

Materials Choice: Based on this comparative analysis of properties and the realities of the availability of fibers in the marketplace[1], the two key candidate materials initially considered for the ECC are: (i) a thin copper wire with a polyethylene sheath; and (ii) polyacetylene filament with a polyethylene sheath [45]. The design evaluation matrix shown in Table 2-3 provides a comparative evaluation of these two candidate materials. The matrix has been derived along the lines of Table 2-2. Based on the relative merits of the fibers shown in the table, the metallic fiber, viz., copper core with polyethylene sheath, has been chosen for the ECC in the Sensate Liner.

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[1] When this research was conducted in late 1996, there were hardly any textile-yarn-based conductive materials in the market. We worked with a company (Saquoit Industries) to identify the properties needed in the conductive yarn and they made samples for our use. Details of the testing and evaluation are covered in Section 3.5. After a few years, Saquoit Industries was bought by another company (Noble Materials) and they introduced the product in the marketplace under the name "X-Static" (http://noblebiomaterials.com/xstatic-textiles/what-x-static/).

Table 2-3 Design Evaluation Matrix for Electrical Conducting Component (ECC)

Weights: %; Score: Scale of 0 (worst) to 4 (best)

Property (Evaluation Criterion)	Weight (%)	Copper Core with Polyethylene Sheath	Polyacetylene Coated Fibers with Polyethylene Sheath
Electrical Conductivity	30	4	1
Stability (Chemical, Thermal, Water)	20	4	1
Resistance to Electromagnetic Interference	15	2	2
Bending Rigidity/Flexural Endurance	10	3	3
Availability	10	4	1
Elongation and Creep Recovery	5	2	3
Weight	5	1	4
Tensile Strength and Modulus	5	4	3
Cost	2.5	3	1
Total and Weighted Score	**100**	**3.43**	**1.73**

2.4.4.3 Materials for Comfort Component (CC)

The Comfort Component (CC) will be in immediate contact with the soldier's skin and will provide the necessary comfort properties for the garment; therefore, the choice of material becomes critical and the chosen material should provide at least the same level of comfort and fit as the undershirt currently issued to soldiers.

The design evaluation matrix for the set of fibers for the CC is shown in Table 2-4. The evaluation criteria have been derived from Figures 2-1 and 2-2. Since the Sensate Liner will be in contact with the body, the material chosen should provide good fabric hand, air permeability, moisture absorption and stretchability to the Sensate Liner and therefore these parameters are weighted high in the table.

As shown in the table, the major fibers evaluated for use in the CC are cotton, Meraklon, microdenier polyester, polyester/cotton blend and Gore-Tex film liner. Meraklon is a polypropylene fiber modified to overcome some of the drawbacks associated with pure polypropylene fibers [46]. Cotton and Meraklon are the two top choices for the CC. Based on the relative merits of the fibers shown in the table, Meraklon has been chosen for the CC in the Sensate Liner. Additionally, since one of the issue items to soldiers is underwear, which is made from polypropylene fibers, the choice of Meraklon for Sensate Liner is further justified.

Table 2-4 Design Evaluation Matrix for Comfort Component (CC)

Weights: %; Score: Scale of 0 (worst) to 4 (best)

Property (Evaluation Criterion)	Weight (%)	Cotton	Meraklon (Polypropylene Fibers)	Microdenier Polyester	Poly-Cotton Blend	Gore-Tex Film Liner
Fabric Hand	15	4	3	3	3	2
Air Permeability	15	4	4	4	4	3
Moisture Absorption	15	4	4	2	3	4
Stretchability (Elasticity/Recovery)	15	3	3	2	2	4
Bending Rigidity	10	3	3	4	3	2
Weight	10	3	4	4	4	4
Tensile Properties	10	2	4	3	3	3
Manufacturability	5	4	4	4	4	3
Cost	5	4	4	1	2	2
Total & Weighted Score	**100**	**3.5**	**3.6**	**3**	**3.1**	**3.1**

2.4.4.4 Materials for Form-Fitting Component (FFC)

The Form-Fitting Component (FFC) will provide the necessary form-fit to the soldier; more importantly, it will keep the sensors in place on the soldier's body during combat conditions. Therefore, the material chosen should have a high degree of stretch to provide the required form-fit and at the same time, be compatible with the materials chosen for the other components of the Sensate Liner.

The Spandex fiber is a block polymer with urethane groups [47]. Its elongation at break ranges from 500 to 600% and thus can provide the necessary form-fit to the Sensate Liner. Its elastic recovery is also extremely high (99% recovery from 2-5% stretch) and its strength is in the 0.6-0.9 grams/denier range. It is resistant to chemicals and withstands repeated machine washings and the action of perspiration. It is available in a range of linear densities and is widely used in swimsuits. Therefore, Spandex has been chosen for the FFC of the Sensate Liner.

2.4.4.5 Materials for Static Dissipating Component (SDC)

The purpose of the Static Dissipating Component (SDC) is to quickly dissipate any built-up static charge during the usage of the Sensate Liner. The charge generated may damage the sensitive electronic components in the PSM Unit. Therefore, the material chosen must provide adequate Electrostatic Discharge Protection (ESD) protection in Sensate Liner.

Nega-Stat, a bicomponent fiber produced by DuPont has a trilobal-shaped conductive core that is sheathed by either polyester or nylon. This unique trilobal conductive core neutralizes the surface charge on the base material by induction and dissipates the charge by air ionization and conduction; it covers the charge dissipation range required of the Sensate Liner [37]. The nonconductive polyester or nylon surface of Nega-Stat fiber controls the release of surface charges from the thread to provide effective static control of material in grounded or ungrounded applications according to specific end-use requirements. The outer shell of polyester or nylon ensures effective wear-life performance with high wash and wear durability and protection against acid and radiation. Therefore, Nega-Stat has been chosen for the SDC in the Sensate Liner.

2.4.5 Evaluation of Manufacturing Technologies

The key manufacturing technologies evaluated for creating the integrated Sensate Liner comprising the various components are shown in the framework in Figure 2-2 along with the corresponding design parameters. These include tubular weaving, in-lay knitting, full-fashioned knitting [48, 49], and embroidery on two different substrates: a knitted fabric and a Gore-Tex film. Table 2-5 shows the design evaluation matrix for the candidate manufacturing technologies.

Table 2-5 Design Evaluation Matrix for Manufacturing Technologies

Weights: %; Score: Scale of 0 (worst) to 4 (best)

Property	Weight (%)	Tubular Weaving	In-lay Knitting	Full-Fashioned Knitting	Embroidery on Knit	Embroidery on Gore-Tex
Form Fitting (Elasticity/ Flexural Endurance)	30	3	4	4	2	3
Fabric Hand	20	3	4	4	2	1
Air Permeability (Breathability)	15	4	4	4	3	1
Durability	10	4	3	3	3	3
Manufacturability	10	3	3	4	3	3
Technology Complexity	10	3	4	2	2	2
Final Sensate Liner Cost	5	2	2	4	3	2
Total	**100**	**3.2**	**3.7**	**3.7**	**2.4**	**2.2**

Since form-fitting and fabric hand are the two principal performance requirements (Figures 2-1 and 2-2), they are weighted high when evaluating the technologies. Tubular Weaving and In-Lay knitting are the two top manufacturing technologies for producing the Sensate Liner. Although Full-Fashioned Knitting (FFK) also ranks high, its technological complexity precludes its usage in the development phase of the Sensate Liner. Moreover, the design of the Sensate Liner is such that the technological complexity outweighs some of the advantages of FFK. Since the two manufacturing technologies (Tubular Weaving and In-Lay knitting) are ranked high and have distinctive characteristics required in the Sensate Liner, they have been selected for producing the Sensate Liner.

Thus, the proposed Design and Development Framework and the methodology have been very effective in translating the “customer’s” broad requirements into a product design and associated engineering design parameters that can be varied (based on underlying fundamental principles) to ultimately arrive at the right materials, the right structure, and the right manufacturing technology to create a Sensate Liner with optimal performance.

2.4.6 The Design and Structure of the Sensate Liner

This structured and analytical process has led to the design of the structure. The Sensate Liner for Combat Casualty Care consists of the following building blocks or modules, which are integrated to create a garment with an integrated information infrastructure that feels and wears like any typical undershirt. The modules are:

- a comfort component to provide the basic comfort properties that any typical undergarment would provide to the user;
- a penetration sensing component to detect the penetration of a projectile;
- an electrical sensing component to serve as a data bus to carry the information to/from the sensors mounted on the user or integrated into the structure;
- a form-fitting component to ensure the right fit for the user; and
- a static dissipating component to minimize static build-up when the garment is worn.

2.5 Research Outcome

A key outcome of the research is the methodology for product design and development in a concurrent engineering environment. In this methodology, customer requirements are translated into appropriate properties that the textile structure must possess to fulfill the requirements. The Properties lead to the specific design for the textile structure. These Properties in the Design are achieved through the appropriate choice of Materials & Fabrication Technologies by applying the corresponding design parameters. All these major facets in the proposed framework are linked together and help the product design team make the logical progression from general ideas to specific parameters and instantiations in a product family.

The elegance of the proposed design of the Sensate Liner lies in the fact that the various building blocks can be put together (like LEGO® blocks) in any desired combination to produce structures to meet specific end-use requirements. For example, in creating a smart garment for healthcare applications, e.g. patient monitoring, the penetration sensing component will not be included. The integration of the desired building blocks will occur during the production process through the inclusion of the appropriate fibers and yarns that provide the specific functionality associated with the building block. In and of itself, the design and development framework resulting from this research represents a significant contribution to systematizing the process of designing textile structures and systems for a multitude of applications. Thus, the textile/apparel industry can adopt this framework for product design in a concurrent engineering environment and become successful in the context of today’s dramatically decreasing "concept-to-market" timeframe and the highly competitive global marketplace.

CHAPTER 3

Development of an Innovative Manufacturing Technology

In this Chapter, we present the manufacturing challenges associated with integrating the plastic optical fiber (POF) into the woven textile structure without any discontinuity to detect projectile penetration on the entire torso of the soldier. We discuss the groundbreaking creation of a three-dimensional garment on a weaving machine. This concept has been enhanced to create a garment with sleeves on the loom. A process to protect the cladding of the POF during its handling in processing has been developed and successfully implemented to maintain the integrity of the optical fibers in the structure. Investigations have been carried out to optimize the structural and material components to arrive at the final specifications of the Sensate Liner.

3.1 Meeting the Challenge: Need for Full-Fashioned Weaving

As discussed in Chapter 2, plastic optical fibers (POF) will serve as the penetration sensing component to detect the penetration of a projectile that could injure the soldier. The optical fiber needs to be laid in the garment with no discontinuities, which means that traditional "cut and sew" operations of garment construction[1] cannot be used for producing the Sensate Liner to detect projectile penetration. Moreover, the POF must be laid closely in the filling direction to cover the torso to detect the penetration of a bullet. Another important requirement is that the POF should continuously cover the

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[1] Typically, a garment, such as a shirt, is made from multiple two-dimensional fabric parts, which are sewn together to create an integrated structure to drape the three-dimensional human body. Consequently, the yarns in the fabrics will be severed in the fabric cutting process and it is not possible to have a single yarn running throughout as an "integral" part of the garment.

entire torso, up to the neck. Since any upper body garment will need armholes to be worn, the POF will have to be terminated at the armhole, which would impair the coverage necessary to protect the portion of the torso above the armhole. Yet another challenge has been to avoid any physical damage to the cladding of the POF due to handling during the production of the Sensate Liner. Such damage would cause signal attenuation and affect the successful operation of the Sensate Liner.

To meet these challenges, research has been carried out on two fronts. The first has focused on developing a process to create a seamless garment on a loom, which, since the advent of weaving, has only produced two-dimensional fabrics. Such a garment without seams is known as a “full-fashioned” garment. The second facet of the research has focused on developing a process to sheath the optical fibers to minimize damage to the cladding during the production of the Sensate Liner.

3.1.1 Concept of a Full-Fashioned Woven Garment

In weaving, two sets of yarns – known as warp and filling yarns – are interlaced at right angles to one another on a weaving machine or loom [50]. Traditional weaving technologies produce two-dimensional fabrics. A garment is three-dimensional because it must drape over and cover the three-dimensional human body. To produce a garment, parts are cut from a two-dimensional fabric and sewn together according to a pattern/style [51]. We now propose the concept of full-fashioned weaving of a garment without seams to enable the integration of optical fibers without cutting and sewing into the Sensate Liner. In the full-fashioned weaving concept, two different weave structures are used as shown in Figure 3-1:

- Tubular structure (Sections A & C);
- Double-layer structure (Section B).

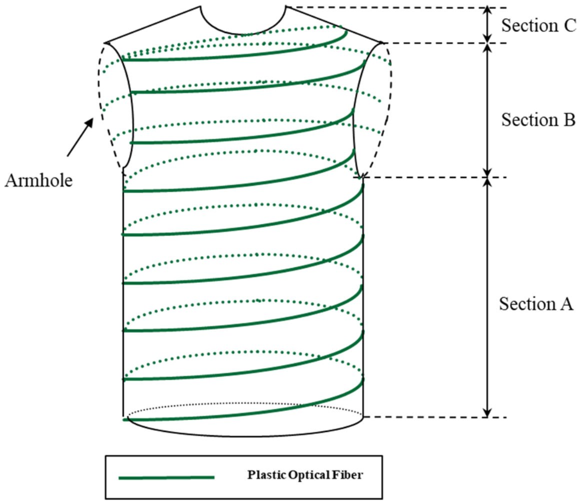

Figure 3-1 Schematic Representation of the Full-Fashioned Weaving Concept

Unlike the structure of a regular shirt made from a woven fabric where the front and back need to be sewn together to make a garment, the tubular structure fabric in the proposed concept ~~e~~merges as an integrated “one piece” garment during the weaving process. In the tubular section of the woven fabric, only one thread or set of threads is interlaced helically and continuously on the front and back.

In the drawing-in-draft[2] for the tubular structure section of the woven fabric, two different sets of warp threads are used alternately – one is for the front and the other is for the back of the fabric. The harnesses of the loom are lifted by the lifting plan[3] representing the front and back of the fabric alternately. Since this is a double cloth

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[2] The drawing-in draft (DID) shows the arrangement of the warp threads in the harnesses of the loom.

[3] The lifting plan provides the sequence of harness movements on the loom.

structure, both the front and back warp threads are placed in the same dent of the reed of the loom.

Although the filling for a tubular fabric needs only one set of continuous threads, the full-fashioned woven garment requires two sets of threads to enable the creation of armholes. The proposed innovative interlacing of the yarns in the double-layer structure section of the garment leads to the creation of the armhole, which is necessary for a garment that is to be worn over the torso.

In the double-layer structure section of the garment, there are two sets of threads, and a double-layer structure is used separately for the front and back of the garment. Since two sets of threads are used from the tubular structure section, the fabric of the double-layer structure section can be woven continuously from the tubular structure section. Likewise, the tubular structure section can be woven continuously from the double-layer structure section. In this manner, for example, a full-fashioned woven garment may be made by continuously weaving a first tubular structure section as described, followed by a double-layer structure section woven from the tubular structure section, and then a second tubular structure section from the double-layer structure section. Moreover, the full-fashioned weaving process concept proposed here is not limited to the manufacture of a sleeveless garment having armholes; it is generally applicable to the manufacture of any full-fashioned garment, which may require similar holes.

3.1.2 Transforming the Concept to Reality

We now discuss the details of transforming the concept of a *woven seamless garment* into reality. Consider a 24-harness dobby loom [50]. We divide the 24 harnesses into six sets with four harnesses in each set. Two of the harnesses in each set are used for the front layer and the other two are used for the back layer of the garment. The lifting plan for the double-layer structure is more complicated than the plan for the first and second tubular structure sections of the garment because of the number of harnesses used to make an armhole for the garment.

3.1.2.1 Description of Tubular Sections A and C of the Garment

Figure 3-2 shows one unit of drawing-in draft, lifting plan and reed plan as well as the design for the tubular structure sections A and C of the garment. As mentioned earlier, the drawing-in draft indicates the pattern in which the warp ends are arranged in their distribution over the harness frames. In the drawing-in draft, two different sets of threads are used alternately – one is for the front F and the other is for the back B of the garment, as shown in the figure. The lifting plan defines the selection of harnesses to be raised or lowered on each successive insertion of the pick or filling. The harnesses of the loom are lifted by the lifting plan representing the front and back of the garment alternately. Since this is a double cloth structure, both the front and back warp threads are placed in the same dent of the reed of the loom. The reed plan in the figure shows the arrangement of the warp ends in the reed dents for the front and back of the garment.

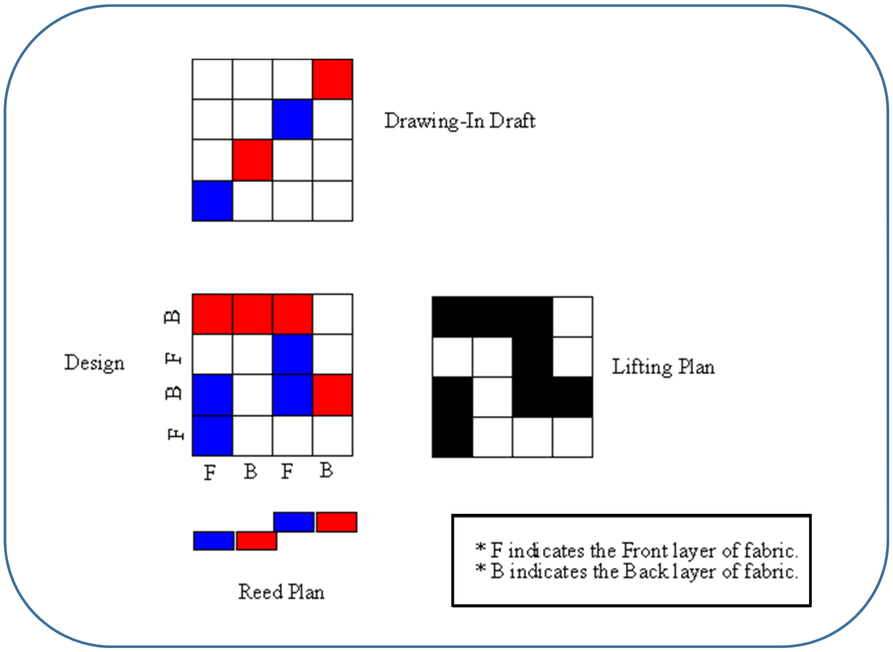
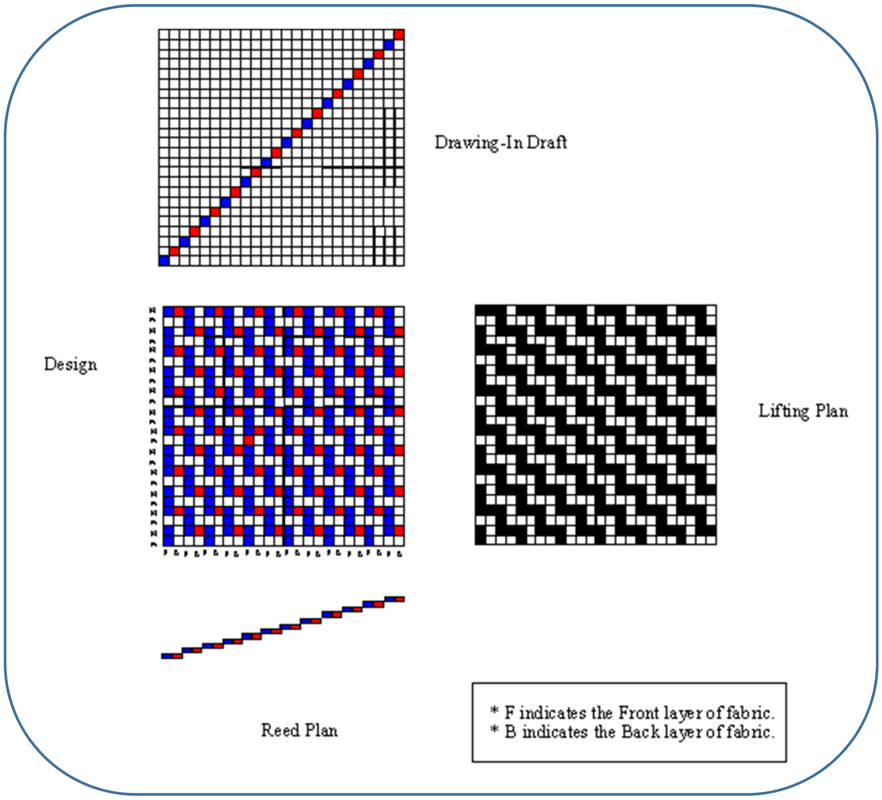


Figure 3-2 Tubular Weave Structure for Sections A & C

3.1.2.2 Description of Double-Layer Section B of the Garment

The armhole is created in Section B (Figure 3-1). In the double-layer structure section B, there are two sets of threads, and a double-layer structure is used separately for the front F and back B of the garment as shown in Figure 3-3.



* F indicates the Front layer of fabric.
* B indicates the Back layer of fabric.

Figure 3-3 Double-Layer Weave Structure for Section B

As illustrated in Figure 3-4, to make an armhole for the garment, the width of each drawing set is sequentially increased and then decreased the same amount (e.g., 0.5 inches) on both sides, and each set of harnesses is dropped in every one inch length of fabric and subsequently picked up in a similar manner. The dropping sequence of the harness sets is 1, 2, 3, 4, 5 and 6 for one-half of the armhole in Figure 3-4. The harness sets also need to be used for the other half of the armhole. The sequence for the harness sets for closing the armhole will be 7, 8, 9, 10, 11 and 12 in Figure 3-4. Since the sequence of drawing-in for both sides of the garment is the same, the armhole is created simultaneously on both sides of the double-layer structure. In this manner, a single continuous woven garment can be produced in which armholes are created, thus resulting in a full-fashioned woven garment.

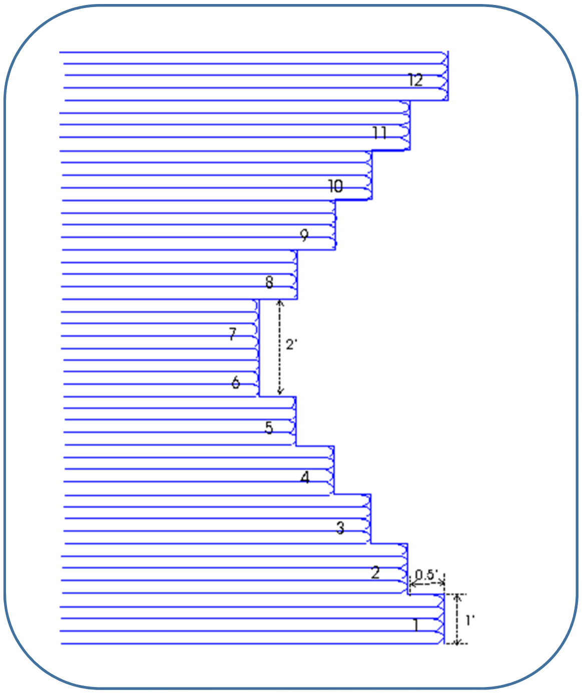


Figure 3-4 Armhole Creation: Dropping Sequence of Harness Sets (1-6) followed by Picking-up Sequence of Harness Sets (7-12)

Since two sets of threads are used from the previous tubular structure section (section A), the fabric of section B can be woven continuously from the fabric of section A. Furthermore, it will be integrated with section C. As a consequence, the POF does not terminate under the armhole – this innovative modification in the weaving process allows for the yarns to continue without termination at the armhole and thereby cover the entire torso of the body. Moreover, there is only one single integrated woven structure that will emerge from the loom and there will be no discontinuities or seams.

3.1.3 Sample Production Using the Novel Full-Fashioned Weaving Process

A 60-inch computer-controlled AVL Industrial Compu-Dobby shuttle loom with 24 harnesses has been used to weave the full-fashioned garment (Sensate Liner). The design has been created using SOPHIS® software and downloaded directly into the shed control mechanism of the loom. Table 3-1 shows the loom configuration for producing the woven garment. Table 3-2 shows the major steps in producing a woven garment on the AVL loom.

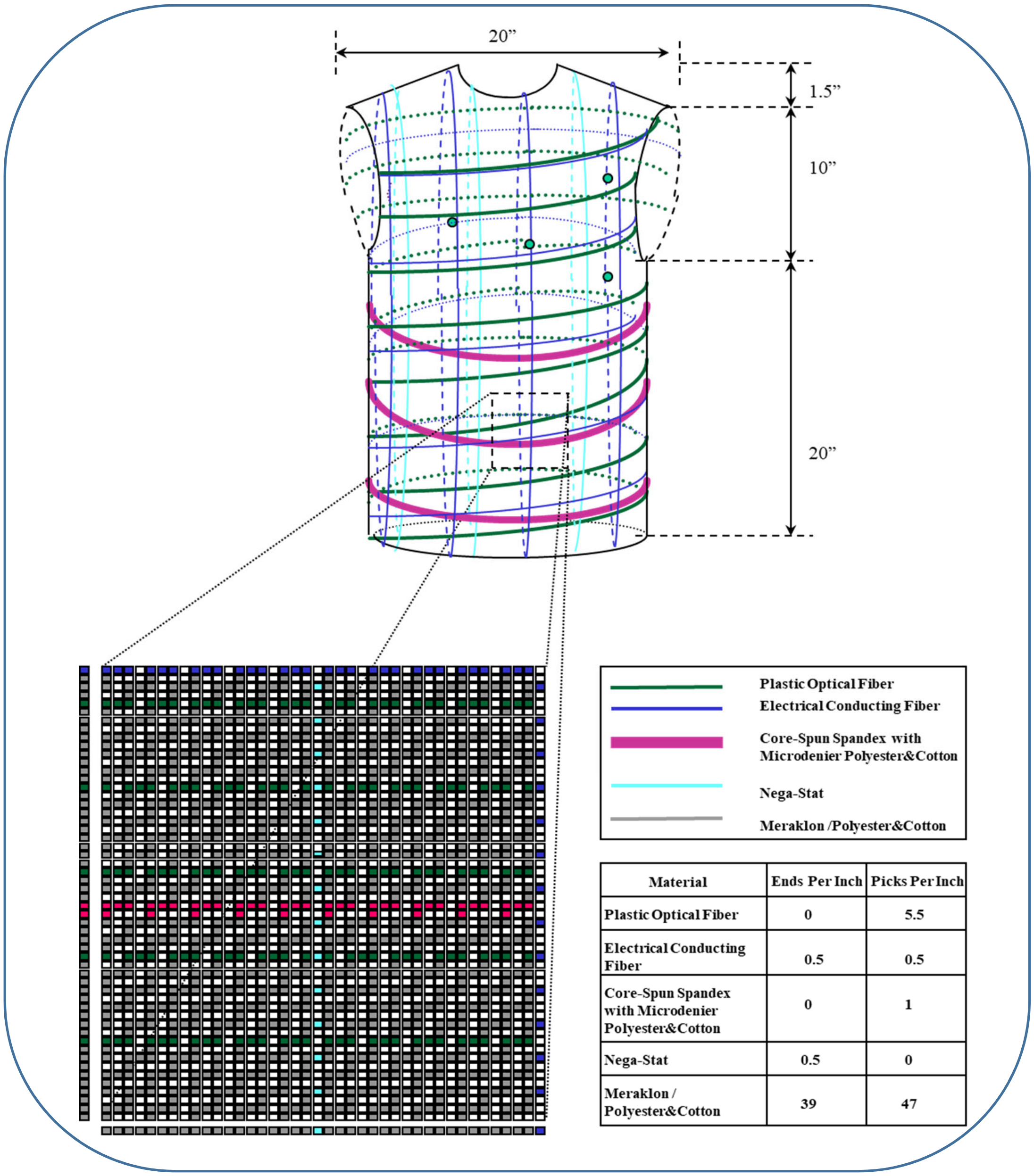
Table 3-1 The Loom Configuration for Full-fashioned Garment

Parameter	Details
Loom Model	AVL Industrial Dobby Loom
Loom Description	Computer-controlled Dobby
Width	60 inches
Number of Harnesses	24
Dents/inch	10
Take-up Mechanism	Automatic Cloth Storage System

Table 3-2 Process Steps in Producing a Seamless Woven Garment on a Loom

1	Enter the Weave pattern in the design Software and download it into the AVL Compu-Dobby.
2	Prepare 160 pirns for 2-inch spacing sectional warp beam.
3	Warp yarns onto sectional warp beam 22-inches wide.
4	Install the required number of drop wires.
5	Draw-in 1600 ends through the drop wires.
6	Draw-in 1600 ends through the heddles of 24 harnesses with Specific Sequences based on the defined weave pattern.
7	Draw-in 1600 ends through the reed.
8	Tie ends onto weaver's beam on each end.
9	Prepare eight bobbins for filling with six shuttles.

Figure 3-5 shows the design of the α-prototype of the Woven Sensate Liner. The various structural components are denoted by the different colors. The legend also shows the relative distribution of yarns for the various components of the garment in a 2" segment.



Material	Ends Per Inch	Picks Per Inch
Plastic Optical Fiber	0	5.5
Electrical Conducting Fiber	0.5	0.5
Core-Spun Spandex with Microdenier Polyester&Cotton	0	1
Nega-Stat	0.5	0
Meraklon / Polyester&Cotton	39	47

Figure 3-5 Design Specifications of the α-prototype of the Woven Sensate Liner

Figure 3-6 shows two views of the α-prototype of the Woven Sensate Liner produced using the full-fashioned weaving concept. It consists of a single-piece garment similar to a regular T-shirt; it fits a 38-40” chest. It is made from the materials selected in Chapter 2 and shown in Figure 3-5. The POF is spirally integrated into the structure during the fabric production process without any discontinuities at the armhole or the seams. Since the POF is present in the entire fabric, including over the armhole, projectile penetration in any part of the entire torso can be detected. This pioneering contribution represents a significant breakthrough in textile engineering because for the first time, a full-fashioned garment has been woven on a weaving machine. This contribution also illustrates the concept that “necessity is the mother of invention” since the full-fashioned process was conceived and developed to avoid discontinuities in the POF that needed to be integrated into the fabric to detect projectile penetration in the Sensate Liner for the soldier.

POF is woven continuously from the bottom to the top of the Sensate Liner.

Figure 3-6 Sensate Liner α-prototype

Left: Sensate Liner showing Armholes, Right: Sensate Liner on a mannequin

3.2 Novel Concept of a Full-Fashioned Garment *with* Sleeves

A further advancement to the full-fashioned weaving concept has been explored for creating a woven garment with sleeves from one single whole fabric (without cut parts) and with no discontinuities or seams. A schematic of the novel full-fashioned garment with sleeves is shown in Figure 3-7. To illustrate the concept, the right sleeve is shown as being open in the figure; however, both sleeves will be closed during the proposed novel weaving process.

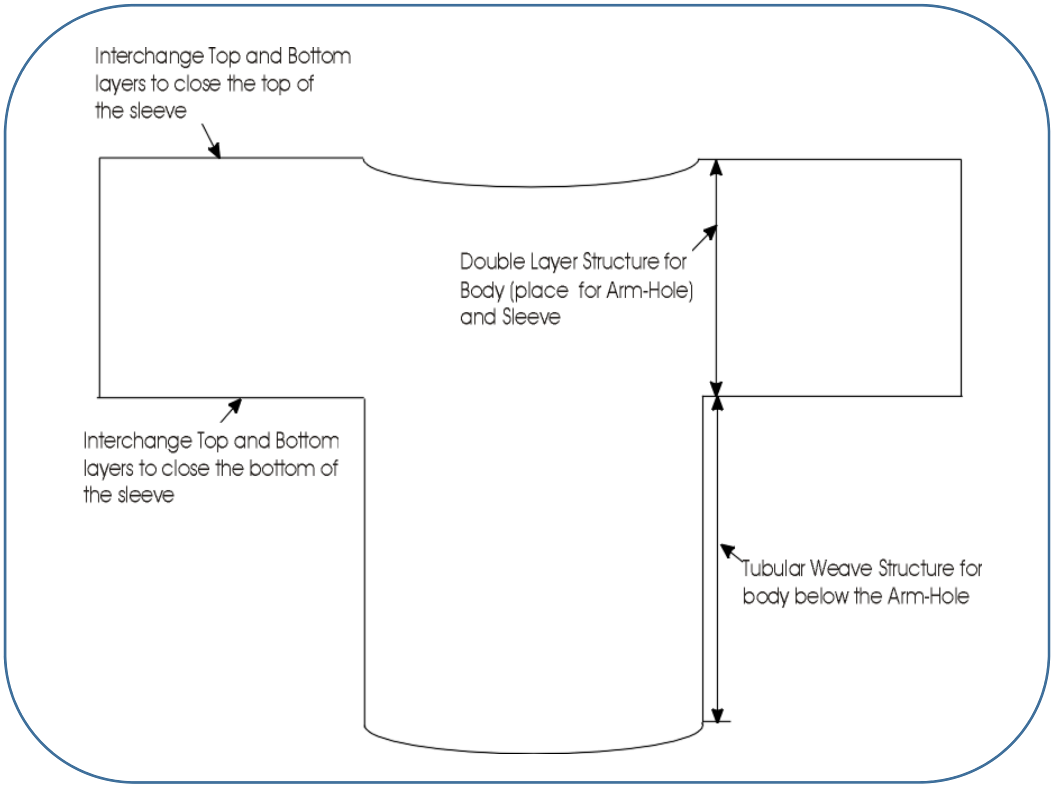


Figure 3-7 Schematic of a Full-Fashioned Garment with Sleeves

As shown in Figure 3-8, three different weave structures are used in the proposed concept for producing the seamless garment with sleeves:

- The first is a tubular structure (Section A);
- The second is a self-stitched layer structure (Section B) and;
- The third is a double-layer structure (Section C)

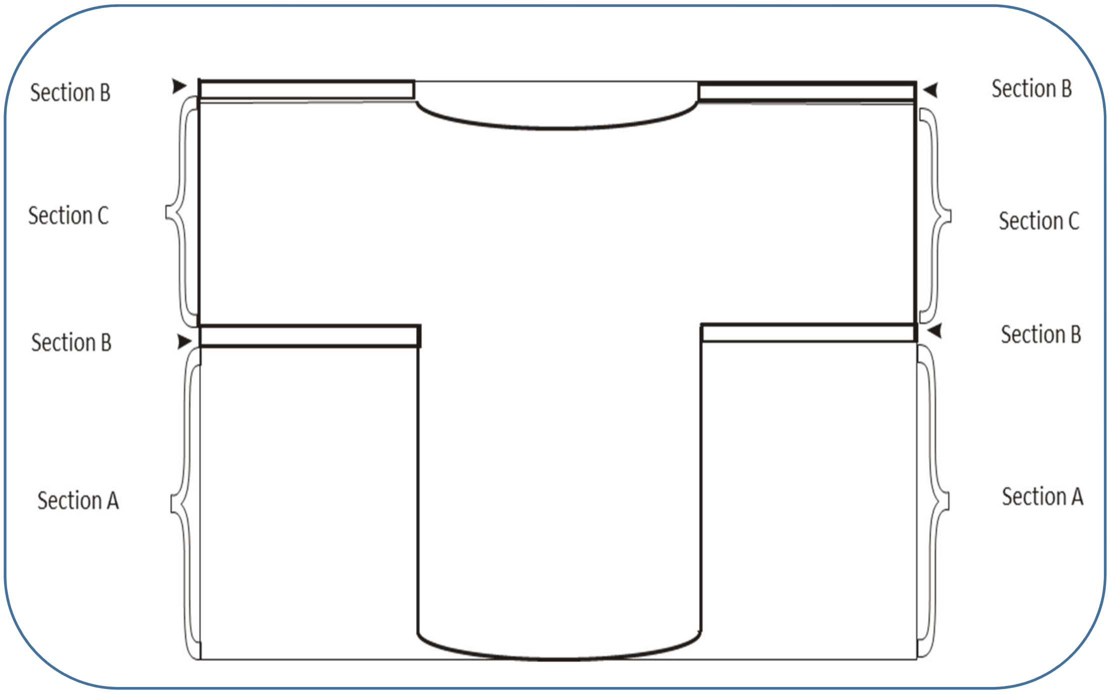


Figure 3-8 Full-Fashioned Garment with Sleeve: Sections with different Weave Structures

In the tubular section of the woven fabric, only one thread or set of threads is interlaced helically and continuously on the front and back. As shown in the drawing-in draft in Figure 3-9, the warp threads are grouped into two sets, one for the body of the garment and the other for the two sleeves. In the drawing-in-draft for the tubular structure section of the body of the woven fabric, two different sets of warp threads are used alternately – one is for the front and the other is for the back of the fabric.

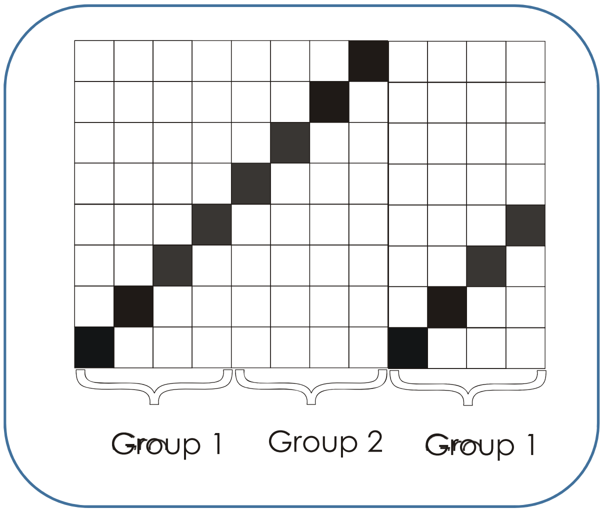


Figure 3-9 Full-Fashioned Garment with Sleeve: Drawing-in Draft

The harnesses of the loom are lifted by the lifting plan representing the front and back of the fabric alternately (Figure 3-10). Since this is a double cloth structure, both the front and back warp threads are placed in the same dent of the reed of the loom. Although the filling for a tubular fabric needs only one set of continuous threads, the full-fashioned woven garment with sleeves requires two sets of threads. This is because of the innovative nature of the double-layer structure section of the garment. In the self-stitched structure section, the front and back sets of warp threads are woven together with the two sets of filling threads creating the closures for the sleeves.

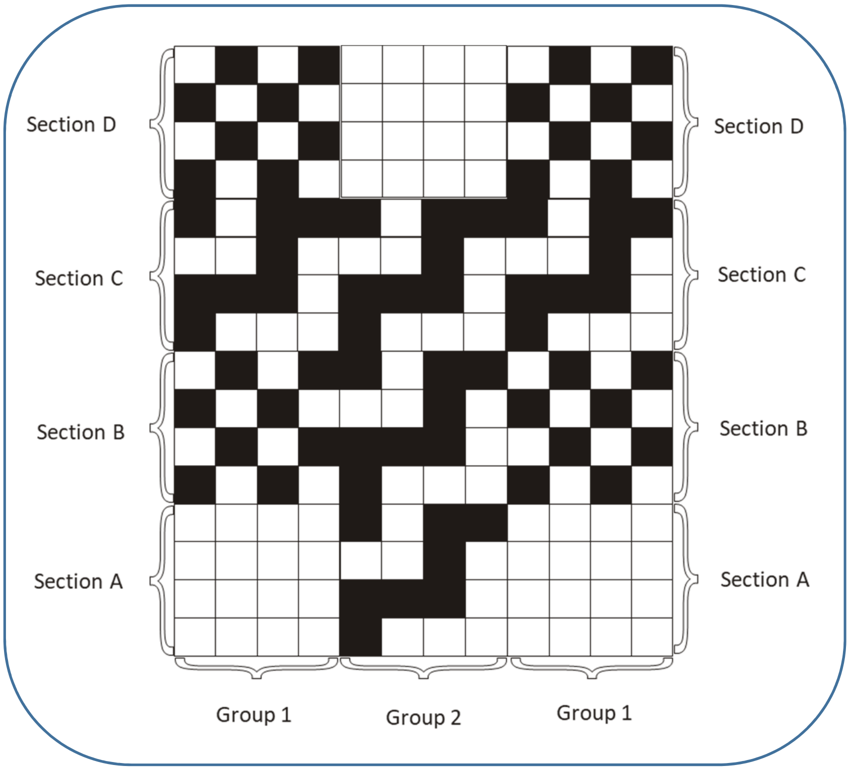


Figure 3-10 Full-Fashioned Garment with Sleeve: Lifting Plan

In the proposed innovative concept, the sleeve is created by way of the self-stitched layer structure section in combination with the double-layer structure section. In the double-layer structure section of the garment, there are two sets of threads, and a double-layer structure is used separately for the front and back of the garment. Since two sets of threads are used from the tubular structure section, the fabric of the self-stitched layer section in combination with the double-layer structure section can be woven continuously from the tubular structure section. Then a stand-alone double-layer structure section can be woven from this combination self-stitched-double-layer structure section.

The stand-alone double-layer structure section can then be followed continuously by another combination self-stitched double-layer structure section. Likewise, the tubular structure section can be woven continuously from this combination self-stitched-double-layer structure section. In this manner, for example, a full-fashioned woven garment may be made by continuously weaving a first tubular structure section as described, followed by a combination self-stitched double-layer structure section, then a stand-alone double-layer structure section followed by a combination self-stitched-double-layer structure section and then a second tubular structure section from the combination self-stitched double-layer structure section. This full-fashioned weaving process for creating a garment with sleeves from the fabric is generally applicable to the manufacture of any full-fashioned garment, which may require similar appendages.

Thus, the developed concept represents another important contribution to textile engineering: The design and production of three-dimensional garments *with* sleeves on a loom.

3.3 Meeting the Challenge: Preserving the Integrity of POF in the Sensate Liner

The POF used in creating the α-prototype of the Sensate Liner has the following properties: The PMMA (polymethyl methacrylate) core of the fiber has a diameter of about 225-255 microns, and a fluorinated polymer as its cladding material with a cladding diameter of about 235-265 microns. The numerical aperture is 0.5, the allowable bending radius is 9 mm, and attenuation is 0.18 dB/m (650 nm).

Attenuation is defined as the loss in power when light passes through POF from one end to the other [52]. The light is propagated by means of Total Internal Reflection. As shown in Figure 3-11, Total Internal Reflection takes place when the angle of incidence is greater than the critical angle of the medium. The critical angle is the angle of incidence at which the angle of refraction is equal to 90°. The critical angle of a medium can be calculated by Snell's equation:

$$n_1 \sin ø_1 = n_2 \sin ø_2$$

where n_1 and n_2 are the refractive indices of the two materials (core and cladding), and $ø_1$ and $ø_2$ are the angles of incidence and refraction, respectively.

When $ø_2 = 90°$,

$$ø_{critical} = \arcsin(n_2/n_1)$$

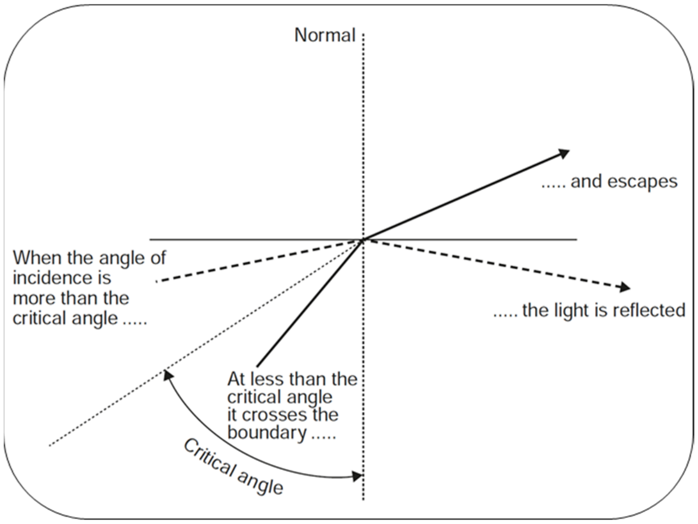


Figure 3-11 Total Internal Reflection [52]

When the fiber is straight (Figure 3-12), the light is incident at an angle greater than the critical angle and results in low attenuation. In the bent position (Figure 3-13), the ray is inside the critical angle causing greater attenuation.

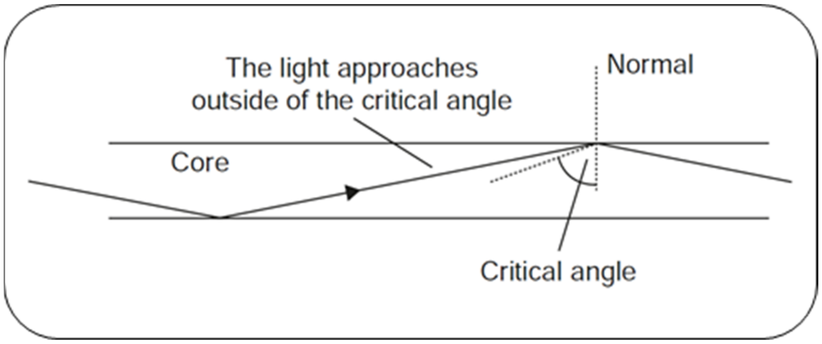


Figure 3-12 The optical fiber is straight [52]

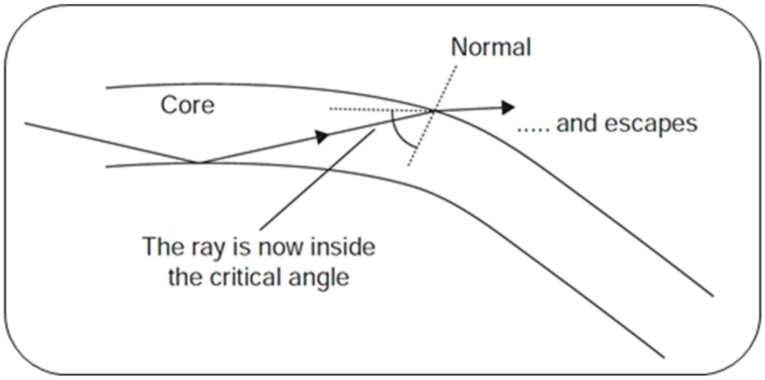


Figure 3-13 The optical fiber is bent [52]

Since the POF is inserted as filling, it bends at the selvedges of the fabric to traverse from one selvedge to the other. So, the signal will be attenuated. Moreover, the cladding of the POF may be damaged during the production process causing additional signal attenuation. To prevent such damage, the POF has been protected with a sheath of polyester/cotton blend fibers using the core-spinning[4] process. Light attenuation studies have been carried out to assess the impact of bending and processing on the performance

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[4] Core spinning is the process of sheathing a core yarn (e.g., POF) with sheath fibers (e.g., Polyester/Cotton). The sheath serves two purposes: It protects the core fiber from damage during handling. Secondly, by choosing a fiber that is comfortable to the skin of the user, the potential discomfort from the core fiber being in direct contact with the skin can be avoided. DREF-3 is a core spinning technology, which has been used to sheath the POF and Spandex in this research.

of POF, which, in turn, provides an assessment of the penetration sensing capability of the Sensate Liner.

3.3.1 Penetration Sensing Capability: Impact of Signal Attenuation

The preliminary testing of the α-prototype of the Sensate Liner revealed that the laser beam sent from one end of the POF attenuated quite severely inside the prototype and was completely dampened after two spirals. The sources of damages hypothesized included microbending, cracking and breaking. Therefore, POF has been tested under controlled conditions to determine the specific causes for the attenuation that could then be eliminated to preserve the integrity of the fibers and ensure the performance of the Sensate Liner to detect projectile penetration.

The benchtop setup for testing the penetration sensing capability of the α-prototype is shown in Figure 3-14. It consists of a Helium-Neon Laser attached to a precision mount that can be accurately positioned at any point in space for precise focusing. The wavelength of the laser is 638 nm and this corresponds to the wavelength that causes minimum attenuation of light inside POF [52].

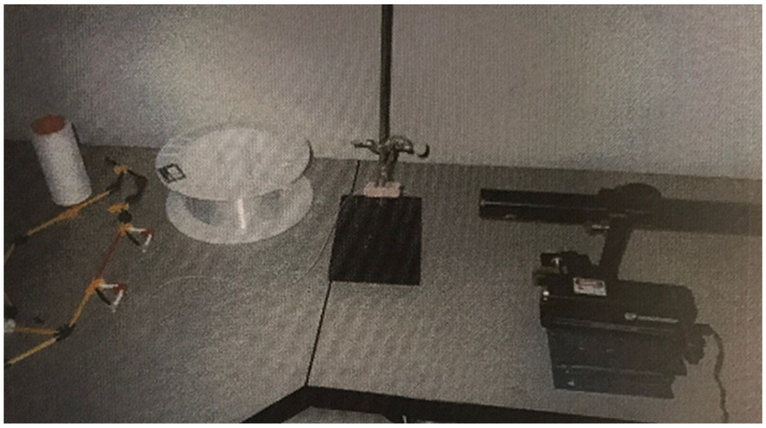

Figure 3-14 Experimental Set-up for Measuring Signal Attenuation in POF

3.3.2 Effect of Bending Radius on Attenuation

The first step in identifying the cause for the attenuation has been to investigate the effect of bending radius on the attenuation of bare and core-spun POF yarns. The yarns were bent at different radii ranging from 6” to 2 mm (the minimum bending radius inside the Sensate Liner is 2.5 mm). The testing revealed that pure bending does not cause the severe attenuation that was observed in the α-prototype. Significant light loss in the form of bright glow-spots was observed in the core-spun yarns at zones where the POF was fractured during the core-spinning process. A similar pattern of light loss was observed inside the α-prototype at points where the POF was damaged during the weaving process.

Thus, there are two potential sources of damage to the POF yarns during processing, viz., core-spinning and weaving; and these are suspected to be the key causes for the severe light attenuation inside the woven α-prototype. Therefore, additional tests have been carried out to study the specific reasons for the attenuation in the spinning and weaving processes using controlled experiments. The findings would help identify and develop appropriate corrective measures to avoid POF fracture during handling. The experimental design for this study is shown in Table 3-3.

Table 3-3 Experimental Design for Identifying Sources of Light Attenuation

Design Parameter	Levels
Ends per Inch	15, 22 & 30 ends/inch
Picks per Inch	15, 22 & 30 picks/inch
Weave Structure	Plain & Sateen
Type of beat-up	Before & After Closing the Shed
Sample Size	2 per combination (36 total)

36 samples have been woven and light attenuation studies conducted at the Laser Dynamics Laboratory in the School of Chemistry and Biochemistry. The experimental setup was similar to the bench-top set-up used earlier; the power of the laser output was measured using a laser power meter coupled to an oscilloscope. The test results are shown in Table 3-4.

Table 3-4 Light Attenuation in Bare, Core-Spun and Woven POF

Fiber Type	**Light Attenuation (db/m)**
Bare Fiber	300
Core-Spun Fiber	10000
Woven Core-Spun Fiber	Complete attenuation after one meter

The results show that there is very severe attenuation in the core-spun and woven POF fibers. The damage during processing and handling of POF could have caused this attenuation. Therefore, to specifically identify and isolate the causes for attenuation, SEM (scanning electron microscope) studies have been carried out.

3.3.3 SEM Studies

SEM studies have been carried out on the bare, core-spun and woven POF. The SEM photographs of 0.04 mm bare and core-spun POF at 200 magnification are shown in Figures 3-15 and 3-16, respectively.

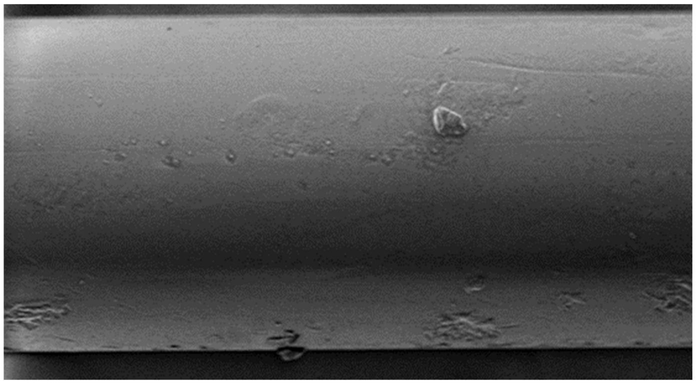

Figure 3-15 Plastic Optical Fiber before Core-Spinning

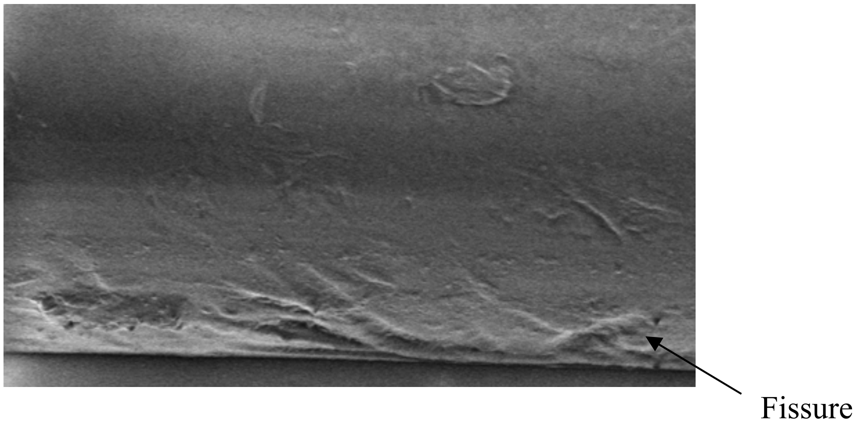

Figure 3-16 Plastic Optical Fiber after Core-Spinning

As seen in the figures, there were severe surface fractures in the core-spun POF. The spiral fissure grooves indicated that the cladding had fractured. Additional damage could also have occurred during the unwinding of the POF from the pirns or during beat-up in the weaving process.

3.3.4 Investigation of the Mechanical Properties of POF

Since the POF had fractured during processing, the mechanical properties of the bare and core-spun POF have been evaluated to assess the loss in mechanical properties caused by processing. Three different samples of POF have been tested.

Sample 1: Plastic Optical Fiber before Core-Spinning

Sample 2: Plastic Optical Fiber after Core-Spinning but without sheath

Sample 3: Plastic Optical Fiber after Core-Spinning with sheath

The mechanical properties were measured using the Statimat® constant rate of elongation strength tester. A gauge length of 200 mm and a rate of elongation of 100 mm/min were used for the study. The results for the three samples are shown in Figures 3-17.

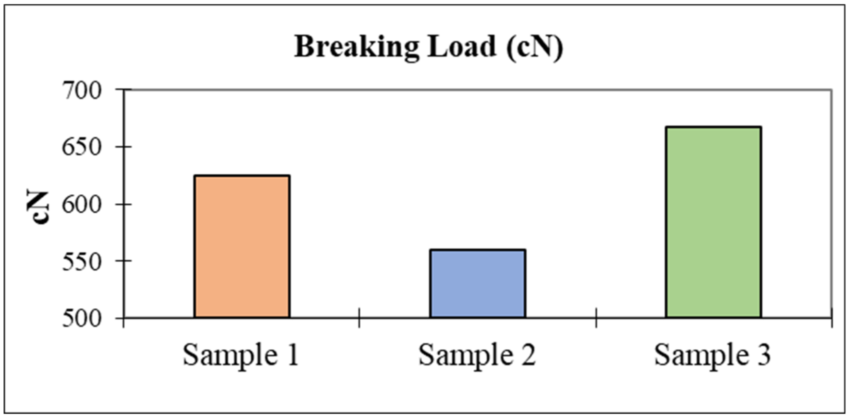

Figure 3-17 Mechanical Properties of POFs

(a) POF Yarn Breaking Load

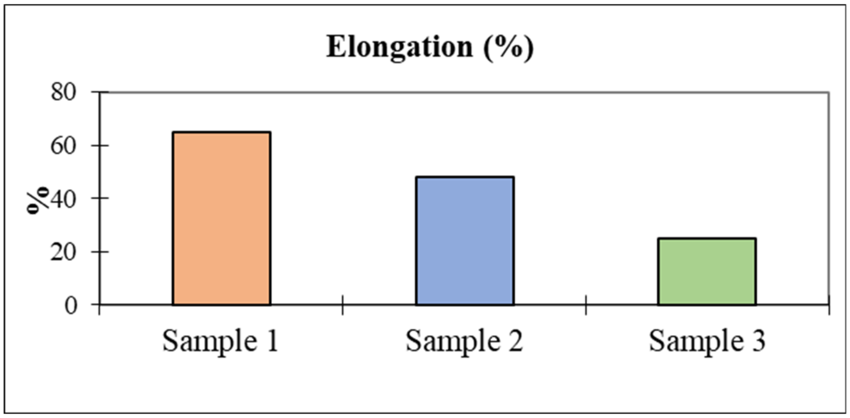

Figure.3-17 Mechanical Properties of POFs

(b) POF Yarn Elongation

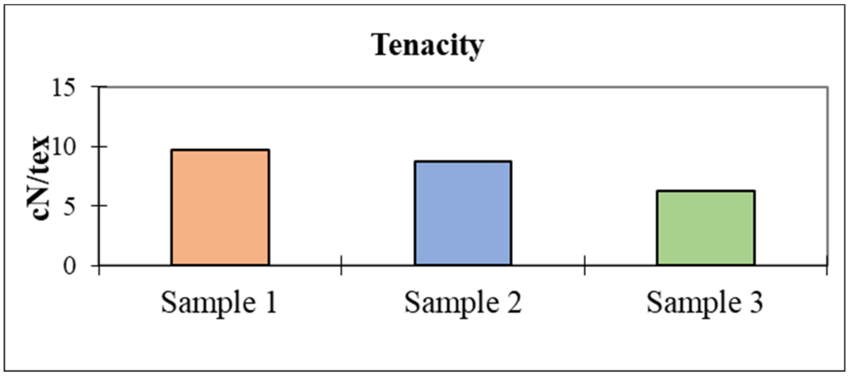

Figure 3-17 Mechanical Properties of POFs

(c) POF Yarn Tenacity

It is clear from the figures that the yarn tenacity decreases after core spinning. The reason for this is that the stresses during the core spinning process fractured the POF creating weak spots and thus decreasing the yarn tenacity; these results confirm the fissures seen in the POF in the SEM studies discussed earlier. However, the tenacity of the core-spun yarn is adequate for forming the garment. The yarn elongation also decreased after core spinning (both before and after the sheath was removed). However, the loss in elongation will not make the POF so stiff that it cannot be used in the Sensate Liner.

3.3.5 Process Improvements to Minimize Damage to POF

Based on these studies and a close visual examination of the α-prototype, the causes for POF fracture have been determined to be as follows:

1. Warp entanglement caused by yarn hairiness;
2. Sharp bending curvature resulting from weft insertion during weaving; and
3. Distortion at the nip rollers during core spinning.

The following process improvements have been made to address these problems.

3.3.5.1 Minimize Entanglement of Warp Yarn

To minimize entanglement caused by warp yarn hairiness, double waxing at the yarn production stage was tried; however, this was unsuccessful due to the stiffness of the Meraklon® fibers. Hence, it was decided to size the warp beam before weaving to eliminate warp entanglement. The sizing (slashing) was carried out at Dundee Mills, GA, after consultations with experts at Dundee Mills and Siedel Inc., a leading sizing company. Sizing propylene spun yarns was fairly novel and therefore Ciba-Sandoz and Amoco Fibers and Fabrics[5] were also consulted. A warp beam with 1680 yarns was prepared in the lab and taken to Dundee Mills for sizing using PVA (Polyvinyl Alcohol).

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[5] Amoco was sold to Monitor Clipper Partners in 1999 (https://www.nytimes.com/1999/08/28/business/company-news-bp-amoco-fabrics-unit-to-sell-operations.html).

Sizing was carried out at different temperatures, speeds and machine settings by master technicians at Dundee Mills to identify the optimal process conditions. However, due to the fiber properties and lack of prior published/available information on the topic, the process was ineffective. Therefore, it was decided to replace Meraklon with polyester/cotton warp to minimize damage to the POF and avoid the problems due to yarn hairiness in weaving.

3.3.5.2 Minimize Sharp Bending of POF in Weaving

To address the issue of bending curvature, two separate POFs have been used one for the top and another for the bottom layer of the fabric. This would minimize the sharp bending of POF seen in the α-prototype.

3.3.5.3 Sheathing of POF to Prevent Damage

Since core-spinning damages the fiber, alternate methods of sheathing or jacketing POF have been investigated. The preferred jacket or sheath material is one that is flexible and will not irritate the skin of the wearer when it comes into contact with the wearer. The sheath material must be thin; the preferred sheath diameter to ensure its wearability is equal to the diameter of the POF plus 0.5 to 1.0 mm, providing a sheath thickness of 0.25 mm and an outer diameter of 1.5 mm. While both a transparent sheath and an opaque sheath will protect the POF, there are several advantages to a transparent sheath material: Points of damage along the POF caused during usage or manufacturing can be visually identified; the intensity of light transmitted throughout the POF can be monitored; and, if desired for certain applications, glowing of the POF can be viewed. Attempts to find a clear sheathed POF in the marketplace were not successful. During discussions with engineers at Toray Industries in Japan, it was learned that they made only opaque sheathed POF, which would not meet the need. So, an in-depth search for a transparent sheathing material was carried out. PVC (polyvinyl chloride) tubing has been found to be a suitable sheath that met the desired target metrics of transparency, thickness, and diameter mentioned earlier. So, it has been chosen as the sheath to protect the POF during the production process. The sheath has been manually sleeved over the required quantity of POF for producing the samples.

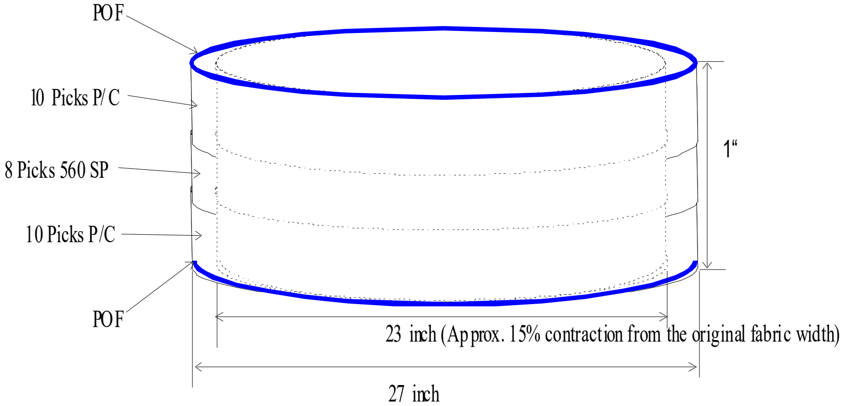
3.4 Design Enhancements and The Second Generation Woven β-Prototype

Once the material and method to protect POF were determined, research focused on creating a β-Prototype: Investigating the materials and structural distribution of the comfort and form-fitting components of the Sensate Liner. Several systematic trials have been carried out to improve the garment appearance, wear and performance. Spandex yarn has been used for the form-fitting component and polyester/cotton yarn for the comfort component. For the structural distribution studies, the role of pick densities in the fabric (since yarns of varying diameters have been used thereby affecting the beating force during the manufacturing process) have been evaluated. Table 3-5 shows the three different designs in two different sizes of Spandex yarn (240 Denier, 560 Denier) and three different pick densities (8, 10, and 14 picks/inch) in the fabric.

Table 3-5 Materials & Structural Variations for β-Prototype

	Warp		Filling	
	Material	EPI	Material	PPI
Design I	Polyester/Cotton	30	Polyester/Cotton	10
			560 Denier Core-Spun Spandex	8
			Polyester/Cotton	10
Design II	Polyester/Cotton	30	Polyester/Cotton	14
			560 Denier Core-Spun Spandex	14
Design III	Polyester/Cotton	30	240 Denier Core-Spun Spandex	10
			560 Denier Core-Spun Spandex	8
			240 Denier Core-Spun Spandex	10

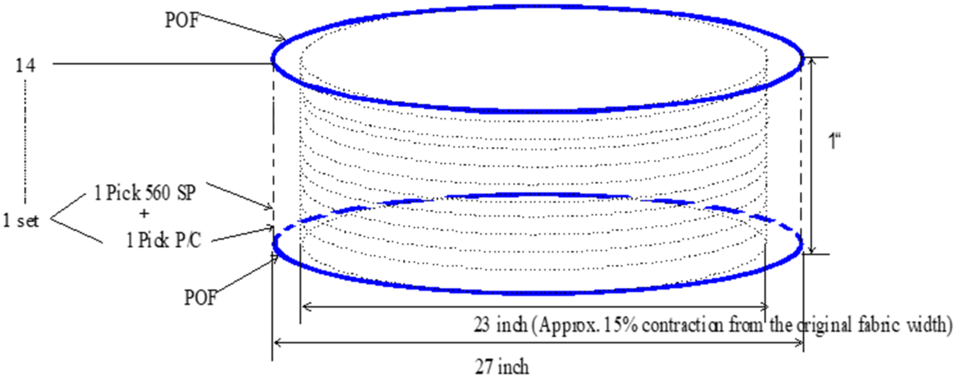
The resulting structures are shown in Figure 3-18. The first design produced a fabric with no differential shrinkage and the third one represented an excellent balance between form and functionality. The third design also incorporated another innovation: Spandex was not used beyond the armhole region since form-fitting characteristics were not critical above that region. The Spandex band shown in the filling direction in Figure 3-18 is the form-fitting component for the tubular woven fabric providing the desired form-fit. These bands behave like "straps", but are unobtrusive and are well integrated into the fabric. There is no need for the wearer to tie something to ensure a good fit for the garment. Moreover, the Spandex band expands and contracts as the wearer's chest expands and contracts during normal breathing. These studies have also led to the selection of the optimum pick densities for the Sensate Liner. Based on the three different variations of samples shown in Figures 3-18, Design II in Table 3-5 gives the most natural form-fit with POF. Thus, the optimal design parameters for the various components of the next generation Sensate Liner have been finalized.



POF	Plastic Optical Fiber
560 SP	560 Denier Polyester/Cotton Core-Spun Spandex
P/C	50/50 Polyester/Cotton blended

Figure 3-18 β-Prototype: Effect of Material and Structural Variations on Performance

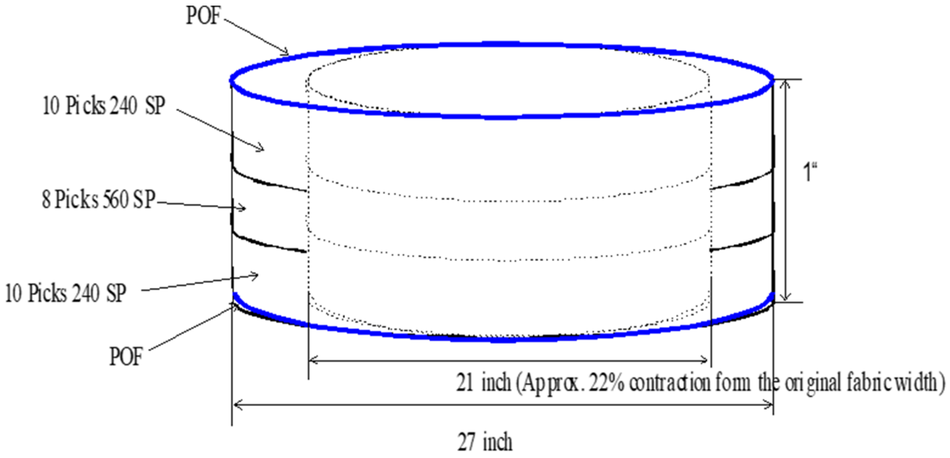
(a) Design I



POF	Plastic Optical Fiber
560 SP	560 Denier Polyester/Cotton Core-Spun Spandex
P/C	50/50 Polyester/Cotton blended

Figure 3-18 β-Prototype: Effect of Material and Structural Variations on Performance

(b) Design II



POF	Plastic Optical Fiber
240 SP	240 Denier Polyester/Cotton Core-Spun Spandex
560 SP	560 Denier Polyester/Cotton Core-Spun Spandex

Figure 3-18 β-Prototype: Effect of Material and Structural Variations on Performance

(c) Design III

3.5 Research Outcomes

In the full-fashioned woven garment produced using the novel manufacturing process, the plastic optical fiber (POF) is spirally integrated into the structure during the fabric production process without any discontinuities at the armhole or the seams. With this innovative process, there is no need for the "cut and sew" operations to produce a garment from a two-dimensional fabric. This pioneering contribution represents a significant breakthrough in textile engineering because for the first time, a full-fashioned garment has been woven on a loom. Since the POF does not terminate under the armhole, the Sensate Liner detects projectile penetration on the entire torso of the soldier. Another novel outcome is that the innovative weaving concept has been enhanced to create garments with sleeves on the loom. A material and method to protect the cladding of the POF during its handling in processing has been developed and successfully implemented to maintain the integrity of the optical fibers in the structure. The material and structural components of the Sensate Liner have been optimized leading to the final specifications.

CHAPTER 4

Information Routing through Textiles: Concept of Interconnections in Textile Structures and Development of Interconnection Technology

In this Chapter, we present the need to route information from sensors in one part of the Sensate Liner to another through the yarns, i.e., the information infrastructure component, in the fabric structure. We propose a novel concept of “interconnections” in a textile structure analogous to those in printed circuit boards (PCB). We develop the technology to make interconnections in fabrics and demonstrate the successful realization of interconnections by transmitting signals to an external monitoring device. We then discuss the need for making such interconnects on a large-scale and propose the concept of “Textillography.” We present two versions of the technology – off-line and on-line.

4.1 The Need: Information Routing through a Textile Structure

In the Sensate Liner, the signals from the various sensors must be routed through the information infrastructure component – the conductive yarns – in the fabric to the common data collection point from which they will be transmitted to the personal status monitor (PSM). The sensors and other devices (e.g., microphone) may be distributed anywhere on the garment; therefore, a “data path” or “information route” must be established in the fabric for the communication channels between the sensors and devices on it and external devices, such as the PSM; which may either be connected physically or via wireless communication. Since the numbers and types of sensors/devices deployed will depend on the end-use application, there is a need for a robust information routing technology for the fabric.

4.1.1 Concept of Interconnection in a Textile Structure

Figure 4-1 shows the schematic of the information infrastructure component (yarn) in the textile structure. It also shows the location of the four sensors (A-D) in the fabric. The information (signals) from these sensors must be routed to the PSM shown at the bottom of the figure. As shown in Figure 4.1(a), there is a direct path from Sensor A to the PSM as shown in the figure through the information infrastructure component (data bus), K. However, there are no direct paths from Sensors B, C and D to the PSM since the respective yarns (the information processing components L, M and N) cannot be connected *directly* to the PSM because of the topology of the textile structure[1]. This means the signals will not reach the PSM.

To create paths for the signals in the fabric, inspiration has been drawn from interconnects in traditional printed circuit boards (PCB). We propose the concept of "interconnections" in a textile structure; such a connection or junction at the intersection of two information infrastructure components will route information from one part of the fabric to another through the intersecting yarns. Figure 4.1(b) shows the interconnection points I_{KX}, I_{LY}, and I_{MZ} in the textile structure that lead to corresponding paths for the signals to flow from the respective Sensors B, C and D to the PSM.

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[1] Incidentally, even in the case of a PCB, multiple layers are required for the traces to connect different points on the board.

Figure 4.1(c) shows a closer look at the transmission path for the signal from Sensor B to the PSM. It first flows through the information processing component L and is then transferred to the information processing component X through the interconnection I_{XL} at the junction of L and X and then on to the PSM.

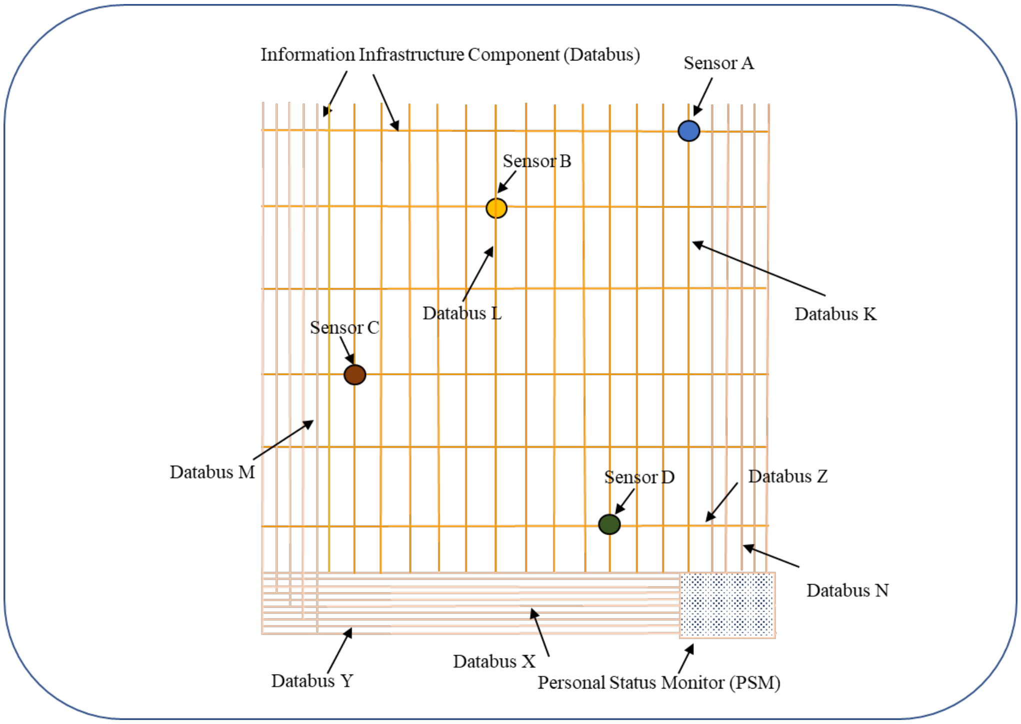

Figure 4-1 Information Routing in a Textile Structure: The Concept of Interconnection

(a) Signal Path from Sensor A to PSM

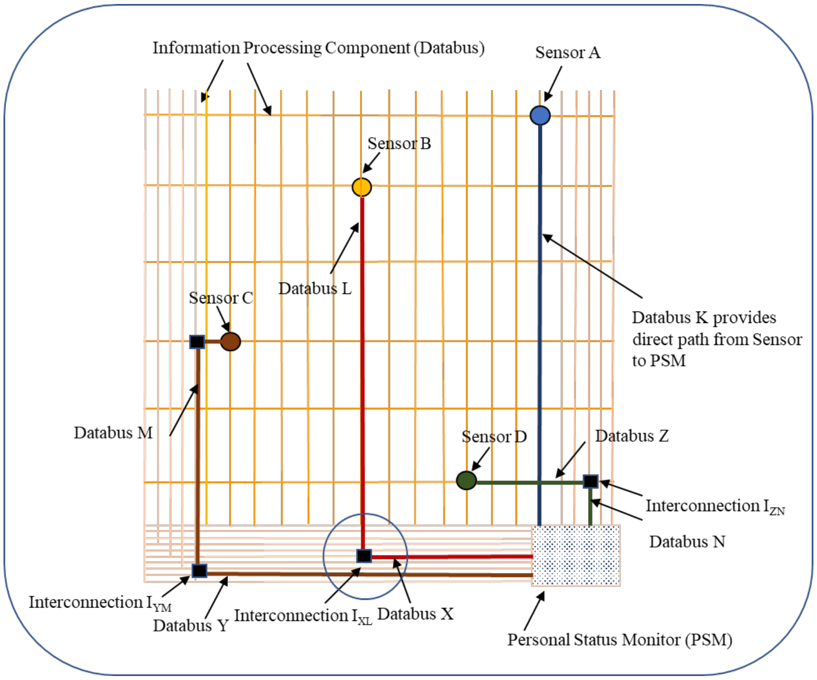

Figure 4-1 Information Routing in a Textile Structure: The Concept of Interconnection

(b) Signals Paths from Sensors B, C and D to PSM through Interconnections

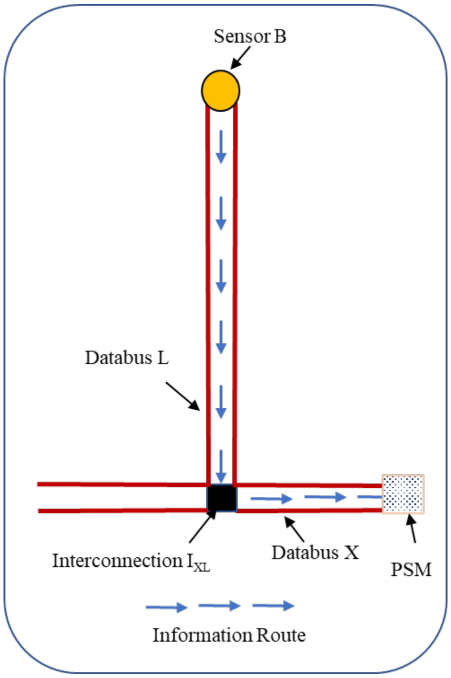

Figure 4-1 Information Routing in a Textile Structure: The Concept of Interconnection

(c) Closer Look at Information Flow through Interconnection I_{XL}

We now discuss the technology developed for realizing the concept of an interconnection or electrical junction at the intersection of two information processing component yarns in the fabric.

4.2 Development of Interconnection Technology

A four-step process has been developed to create interconnections in the Sensate Liner. It consists of the following sequence of operations:

1	Softening and removal of the insulation of the conductive fibers at the desired junction of the two or more intersecting yarns
2	Abrasion of insulation at the junction or interconnection zone;
3	Application of a conductive polymer paste at the junction to establish the interconnection between the conductive fibers
4	Insulation of the interconnection zone to prevent undesirable short circuits.

Optionally, a sensor or connector can be attached at the interconnection point to acquire or transmit the information from that point.

The potential for automation has been a key driving factor in the development of the proposed interconnect process since automation is essential for large-scale production of the Sensate Liner. Moreover, automation is critical for the reproducibility and repeatability of the various steps to create a uniform product on a continuous basis. The details of the four steps are presented now.

4.2.1 Softening and Removal of Insulation

The first step in making an interconnection between the conductive fibers is to remove the insulation of the intersecting yarns at the junction. The interconnection zone is chemically softened for the effective removal of the insulation. The process variables are: (i) the chemical used in the process; (ii) the concentration of the chemical; (iii) the amount of chemical applied; and (iv) duration of chemical application. Acetone (100%) has been chosen as the chemical softening agent and one drop of it is applied. It is allowed to stand for 10 seconds before the next step in the process. These processing conditions ensure that the conductive yarn itself is not damaged. Moreover, since polyester, cotton and spandex (the other components in the Sensate Liner) do not interact with acetone, they are not damaged during this process. When stainless steel is used as the conductive fiber, heat alone is sufficient to achieve the desired softening and removal of insulation.

4.2.2 Abrasion of Insulation

The next step is to abrade the softened insulation at the intersection zone. The setup consists of a vibrating brush[2] that oscillates at 3000 Hz. This effectively strips out the insulation at the interconnection zone as shown in Figure.4-1 (c) The process variables are: (i) the frequency of oscillation of the brush; (ii) the pressure applied during abrasion; and (iii) duration of abrasion. By modifying these parameters, it would be possible to strip out different types of insulation without damaging the conductive yarns themselves.

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[2] A vibrating toothbrush was used for this experiment.

4.2.3 Application of Conductive Paste

The interconnection in the abraded zones is established by applying a conductive paste to close the circuit between the intersecting warp and filling conductive yarns in the fabric. The process variables are: (i) the properties of the conductive paste used in the process; and (ii) the quantity of the paste applied to the interconnect zone. The conductive paste chosen should have the following properties: Have only minimum electrical resistance, adhere well to the conductive yarns, and should not chemically react with the conductive yarn. Three types of conductive pastes/ink have been evaluated for making the interconnections; these are:

- Magnolia Plastics: Magnobond 3870 Part A and Part B
- Magnolia Plastics: Magnobond 8005, Part A and Part B
- Colortronics: TXFS-007 Conductive Ink

Magnobond 3870 Part A and B is a two-part silver-filled epoxy conductive adhesive. According to the manufacturer (Magnolia Plastics[3]), it has better tensile strength and lower resistance than other traditional silver-filled systems. Its properties are shown in Table 4-1.

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[3] Magnolia Plastics is now Magnolia Advanced Materials, Inc. [http://magnolia-adv-mat.com]

Table 4-1 Properties of Magnobond 3870 Conductive Paste

Specific Gravity	Part A: 1.7, Part B: 1.0, Mix: 1.6
Mix Ratio	Part A: Part B = 100:4
Cure Schedule	24 hours at room temperature
Pot Life	60 minutes
Lap Shear Strength at 75° F (ASTM D 1002)	2000 psi
Volume Resistivity at 75° F	4.0×10^{-3} ohm-cm
Boiling Point	> 225 °F
Vapor Density	> 1

The effects of cure temperature, curing time, and mix ratio of Parts A and B of the conductive paste on the resistivity of the resulting interconnection have been investigated. The results are shown in Table 4-2.

Table 4-2 Effect of Cure Temperature, Curing Time and Mix Ratio (A:B) on Resistivity (ohm-cm) of Magnobond 3870

Cure Temperature (° F)	Curing Time (hour)	Mix Ratio (A:B)			
		50:4	100:4	150:4	200:4
75	5	4.1×10^{-3}	4.2×10^{-3}	4.2×10^{-3}	4.3×10^{-3}
75	4	4.2×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	4.2×10^{-3}
75	3	4.1×10^{-3}	4.2×10^{-3}	4.2×10^{-3}	4.2×10^{-3}
150	1.5	4.2×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.1×10^{-3}
150	1	4.1×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	4.2×10^{-3}
150	0.5	4.2×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.2×10^{-3}

Magnobond 8005 is a two-part 100% silver filled epoxy adhesive (Part A and Part B); it is designed to have a high degree of electrical conductivity and good adhesion. Its properties are shown in Tables 4-3.

Table 4-3 Properties of Magnobond 8005 Conductive Paste

Mix Ratio: Part A: Part B = 100:57
Cure Schedule: 24 hours at 75° F, 30 minutes at 210° F
SPI Classification: Part A: 4; Part B: 4
Lap Shear Strength (ASTM D1002): 1400 psi at 75° F, 1350 psi at 210° F
Volume Resistivity: 5.0 x 10^{-4} ohm-cm at 75° F, 6.0 x 10^{-4} ohm-cm at 210° F
Operation Temperature: -80° F to 400° F

The effects of cure temperature, curing time, and mix ratio of Parts A and B of the paste on the resistivity of the resulting interconnection have been investigated. The results are shown in Table 4-4.

Table 4-4 Effect of Cure Temperature, Curing Time and Mix Ratio (A:B) on Resistivity (ohm-cm) of Magnobond 8005

Cure Temperature (° F)	Cure Time (hour)	Mix Ratio (A:B)			
		50:50	100:50	150:50	200:50
75	12	5.1 x 10^{-4}	5.1 x 10^{-4}	4.9 x 10^{-4}	5.1 x 10^{-4}
75	24	5.0 x 10^{-4}	5.1 x 10^{-4}	5.0 x 10^{-4}	5.2 x 10^{-4}
75	36	5.1 x 10^{-4}	5.1 x 10^{-4}	5.0 x 10^{-4}	5.1 x 10^{-4}
210	0.25	5.8 x 10^{-4}	6.0 x 10^{-4}	6.0 x 10^{-4}	6.0 x 10^{-4}
210	0.5	6.1 x 10^{-4}	6.1 x 10^{-4}	6.0 x 10^{-4}	6.1 x 10^{-4}
210	0.75	6.1 x 10^{-4}	6.1 x 10^{-4}	6.0 x 10^{-4}	6.1 x 10^{-4}

Colortronics TXFS-007 is a screen-printable conductive ink. It is a water-based ink and its properties are shown in Table 4-5.

Table 4-5 Properties of Conductive Ink Colortronics TXFS-007

Mix Ratio	2.0 % to 2.5 % Cross linker AC-001 per weight of TXFS-007
Viscosity	5000 cps to 8000 cps at 10 RPM
Cure	• 3 minutes at 100 ºF; • 6 seconds at 100 ºC by IR Lamp then 3 minutes at 100 ºF
Conductivity	less than 1 Kohm/sq at 25 microns

A large number of interconnections with various combinations of conductive paste (amount, location of application, curing conditions, etc.) has been produced and tested. It has been found that the Magnabond interconnections were very stiff and brittle; this was due to the higher percentage of the component B in the paste. Moreover, the quality of the interconnection deteriorated with washing for the conductive ink samples. Therefore, Magnobond 3870, a silver-filled eposy (Mix Ratio of 100:4) has been chosen as the conductive paste to make the interconnections. It also cures well at room temperature and does not react with the polyamide-based conductive yarn. It was applied to the interconnection zone using a glue gun.

4.2.4 Insulation of the Interconnection Zone

The interconnection zone must be insulated to prevent it from shorting in the presence of water. The insulating layer should not chemically react with the conductive paste, should adhere well to the paste, and should offer adequate insulation. It has been applied to the interconnection zone using a spray gun. A silicone-based spray has been used to insulate the interconnect zone.

4.3 Optimization of the Interconnection Process

One of the key requirements of an interconnection is that it should not affect the integrity of the signals passing through it. This means the interconnection should not introduce any external noise and/or artifacts. Apart from the choice of conductive paste, the other important process parameter that might affect the quality of the interconnection is the location of the conductive paste application. So, the conductive paste has been applied in three different locations with reference to the interconnection point to assess the impact on the quality of the signals:

1. Top of the interconnection point;
2. Bottom of the interconnection point; and
3. Both Top and Bottom of the interconnection point.

Figure 4-2 shows the three locations at which the conductive paste was applied at the interconnection points.

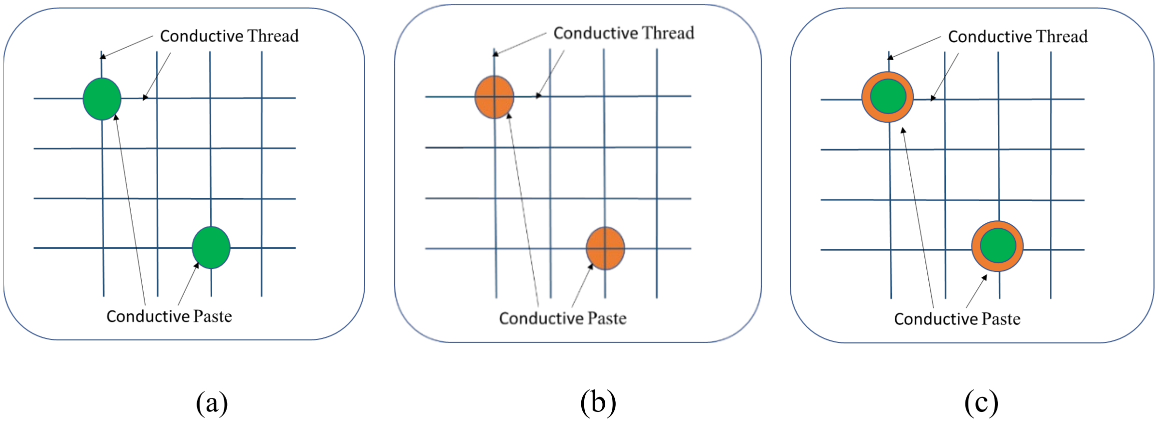

Figure 4.2 Application of Conductive Paste at Interconnection Point
(a) Top; (b) Bottom; (c) Top and Bottom

The quality of the interconnections resulting from the three methods was tested using an oscilloscope; it was found that the third variable – applying the conductive paste on top and bottom – was the optimum one in terms of achieving a leak- and short-circuit-proof interconnection that ensured the high fidelity of the electrical signals.

Thus, a manual interconnection technology has been developed and refined to create electrical junctions to facilitate “plug and play” of sensors and devices in the Sensate Liner. However, as the research progressed, the need for an automated, “scalable” interconnection technology to facilitate the production of Sensate Liners on a much larger scale (quantity) and dimensions (large surface areas) became clear. Such a robust and cost-effective enabling interconnection technology is critical for engineering textile electrical circuits in the fabric. Automation facilitates the reproducibility and repeatability of the various steps to create a uniform product on a continuous basis and in large quantities. Therefore, a conceptual framework for such a technology has been developed. It has been named *Textillography*. Just as stereolithography has revolutionized the design and development of 3-D parts, it is hoped that Textillography will lead to the rapid realization of interconnection architectures in textile structures.

4.4 Textillography: A Novel Technology for Interconnection Architecture in Fabrics

In developing the concept of Textillography, two modes in which the enabling technology can be applied are considered: On the loom and off-the-loom, each with its own set of advantages. For instance, the fabric's topology is defined and better-controlled while it is being produced, making a case for on-loom Textillography. On the other hand, the fabric production process might be adversely affected by the interconnection process (e.g., mismatch in the production speeds of weaving and making interconnections). So, an off-the-loom process might be appropriate. Both modes are built on the manual interconnection technology developed and discussed in Section 4.2.

4.4.1 The Conceptual Framework for Off-the-Loom Textillography

Figure 4-3 shows the sequence of steps in the Textillography process while Figure 4-4 shows the proposed set-up for off-the-loom Texillography.

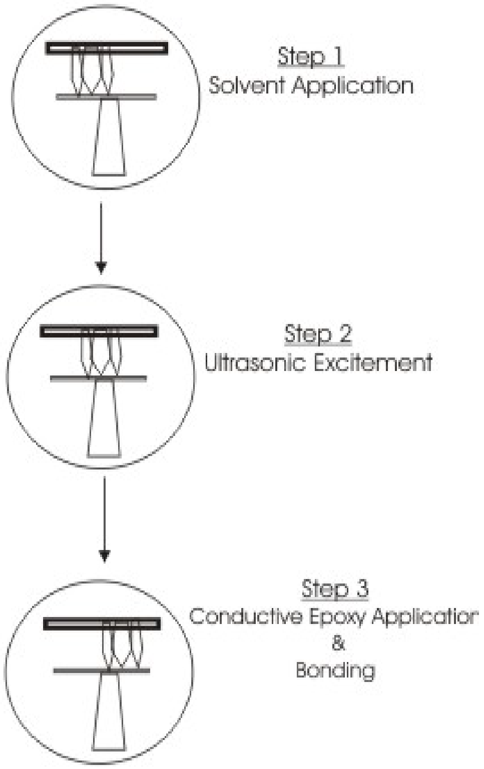

Figure 4-3 Sequence of Steps in the Textillography Process

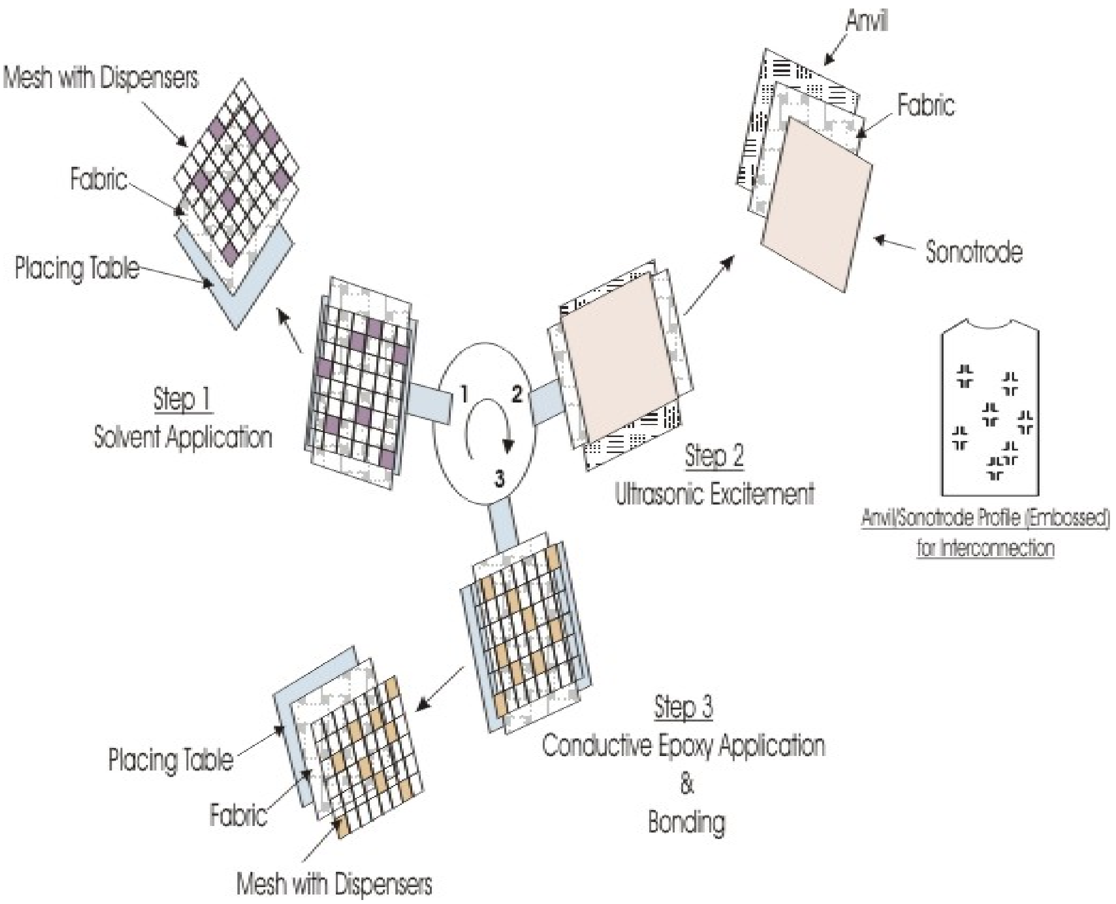

Figure 4-4 Schematic of Off-the-loom Textillography

In Step 1, the solvent is applied at the “desired” interconnection points using the Mesh (with dispensers) that is placed on the fabric. In Step 2, the interconnection points are “excited” using an ultrasonic device to establish the desired contact between the fibers/yarns in the fabric. Figure 4-5 shows the principle of ultrasonic welding.

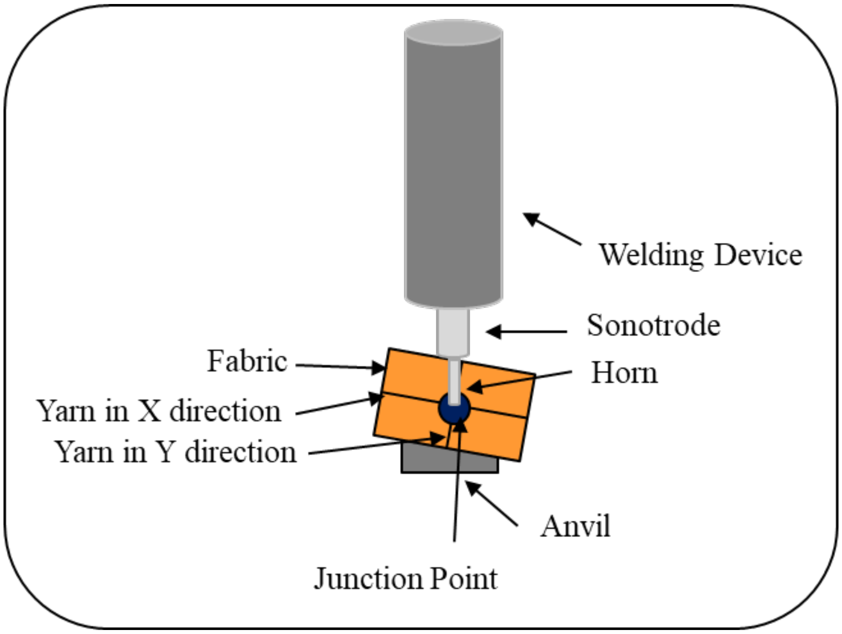

Figure 4-5 Principle of Ultrasonic Welding

The Anvil profile is shown in Figure 4-6 and it resembles the yarn intersection.

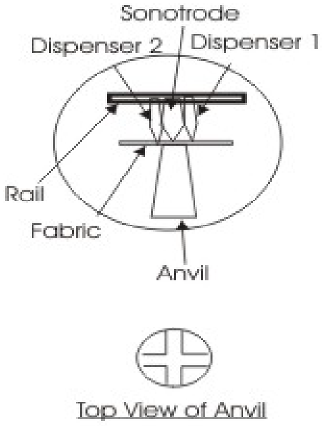

Figure 4-6 The Profile of the Anvil in Textillography

In the final step, Step 3, a conductive epoxy is used to bond and firmly establish the interconnection. The interconnections can be made through chemical bonding, laser etching and bonding, and ultrasonic welding. By building the system around a "turn table" type configuration as shown in Figure 4-3 multiple pieces of fabric can be processed in sequence resulting in an "assembly line" process to facilitate processing of longer and wider lengths of fabric.

4.4.2 The Conceptual Framework for On-Loom Real-Time Textillography

Figure 4-7 shows the proposed set-up and sequence of operations for the on-loom Textillography system. The Textillography device – mounted on a rail – will be positioned in real-time at the desired warp/filling interconnection after the fabric has been formed (after the beater as shown in the figure). In Step 1, the Dispenser containing the solvent moves to the desired interconnection point to dispense the solvent. In Step 2, the sonotrode (with a yarn intersection profile) moves into place to excite the junction. Finally, the conductive epoxy is applied in Step 3. While the illustration is for the ultrasonic process, a similar process will work for chemical bonding and laser-etching and bonding as well. Thus, the proposed "on-loom" Textillography will lead to the realization of interconnection architectures in real-time and in desired configurations.

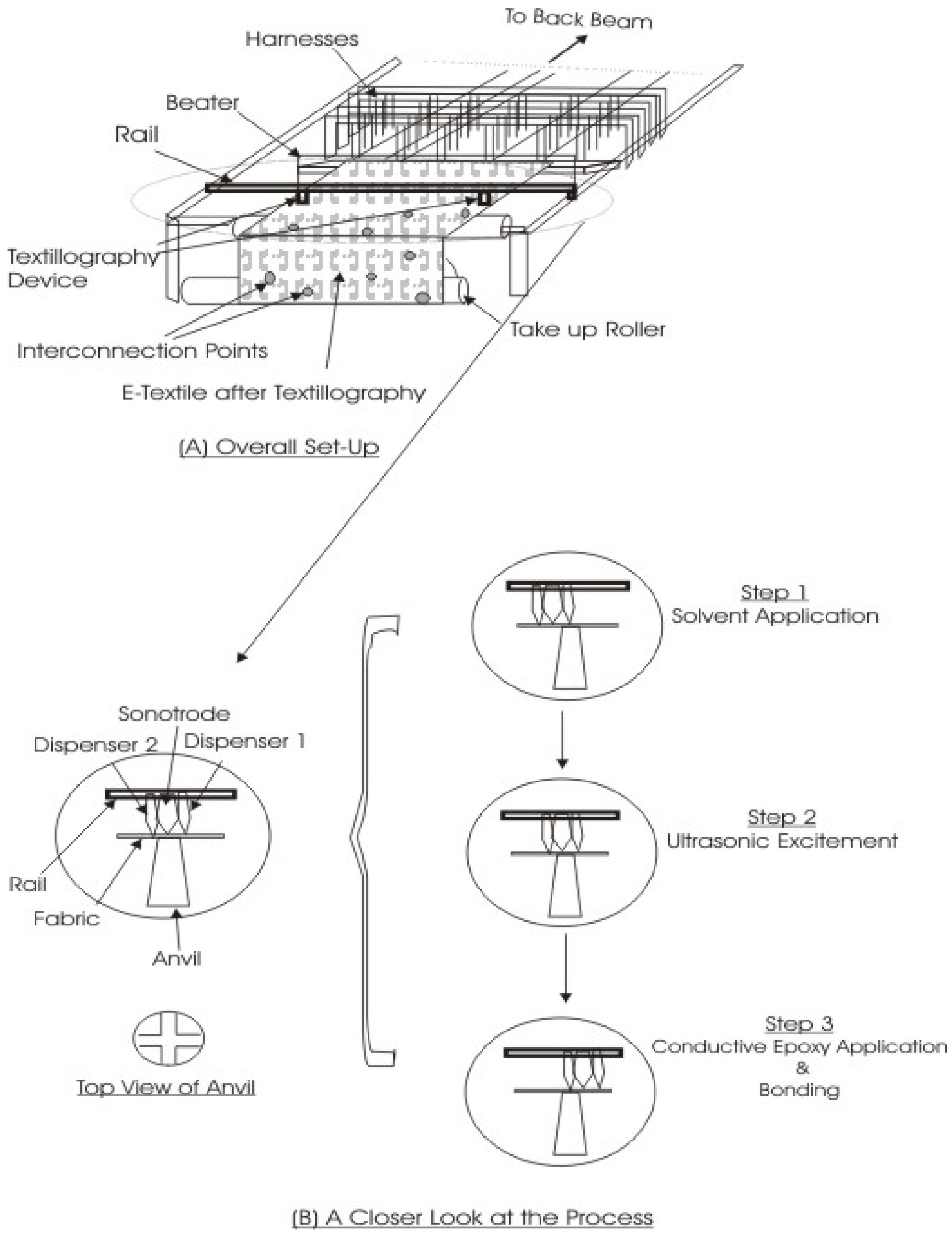

Figure 4-7 Schematic of On-loom Textillography

Figure 4-8 shows the schematic of a network of electric junctions, information routes and sensors that can be created in a fabric using Textillography to meet performance characteristics desired in specific applications.

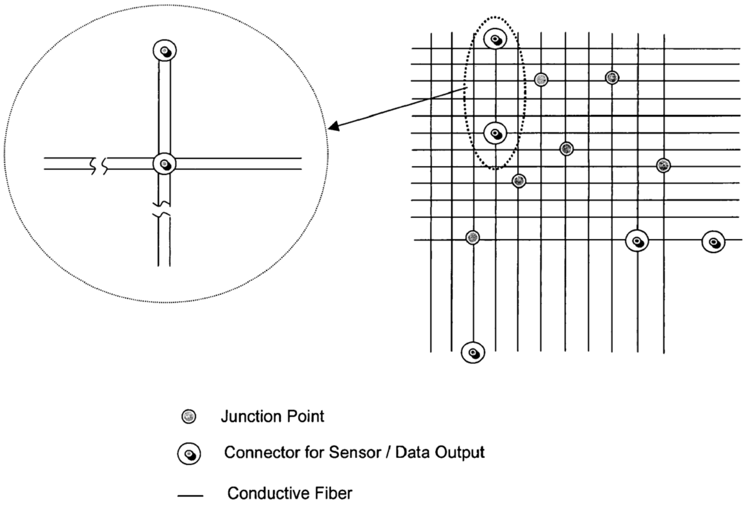

Figure 4-8 A Network of Electrical Junctions, Information Routes and Sensors in a Fabric using Textillography

4.5 Research Outcomes

This facet of the research has led to the novel concept of “interconnections” in a textile structure to seamlessly route information from sensors or devices in any part of the fabric to another through the yarns in the fabric thus creating a flexible textile-based information infrastructure analogous to the PCB. Another novel outcome is an interconnection technology for creating interconnects or electrical junctions in textile structures. Yet another contribution of the research is the concept of Textillography for automating the creation of large-scale interconnects in textile structures.

CHAPTER 5

Investigation on Materials for the Information Infrastructure Component

In this Chapter, we discuss the in-depth studies carried out on the electrical and mechanical properties of conductive fibers – one of the two information infrastructure components in the Sensate Liner. POF is the other information infrastructure component. These fundamental investigations are essential for identifying and selecting conductive materials for the Sensate Liner.

5.1 Guiding Principles for Material Selection

Retaining the “textile look and feel” of the Sensate Liner while ensuring its functionality is important for enabling its acceptance by soldiers. The choice of materials for the various components affects this delicate balance between form and function of the Sensate Liner. As discussed in Section 3.2, the performance requirements of the Sensate Liner govern the final “design” of the structure including the materials, manufacturing technologies, sensors, and processors to be incorporated into the Sensate Liner.

Conductive fibers – integral part of the data bus – are at the heart of the Sensate Liner and directly affect not only the performance of the structure but also the realization of the structure in the first place. Figure 5-1 shows the key factors that should be considered in the selection of conductive fibers to meet the desired performance characteristics of the Sensate Liner.

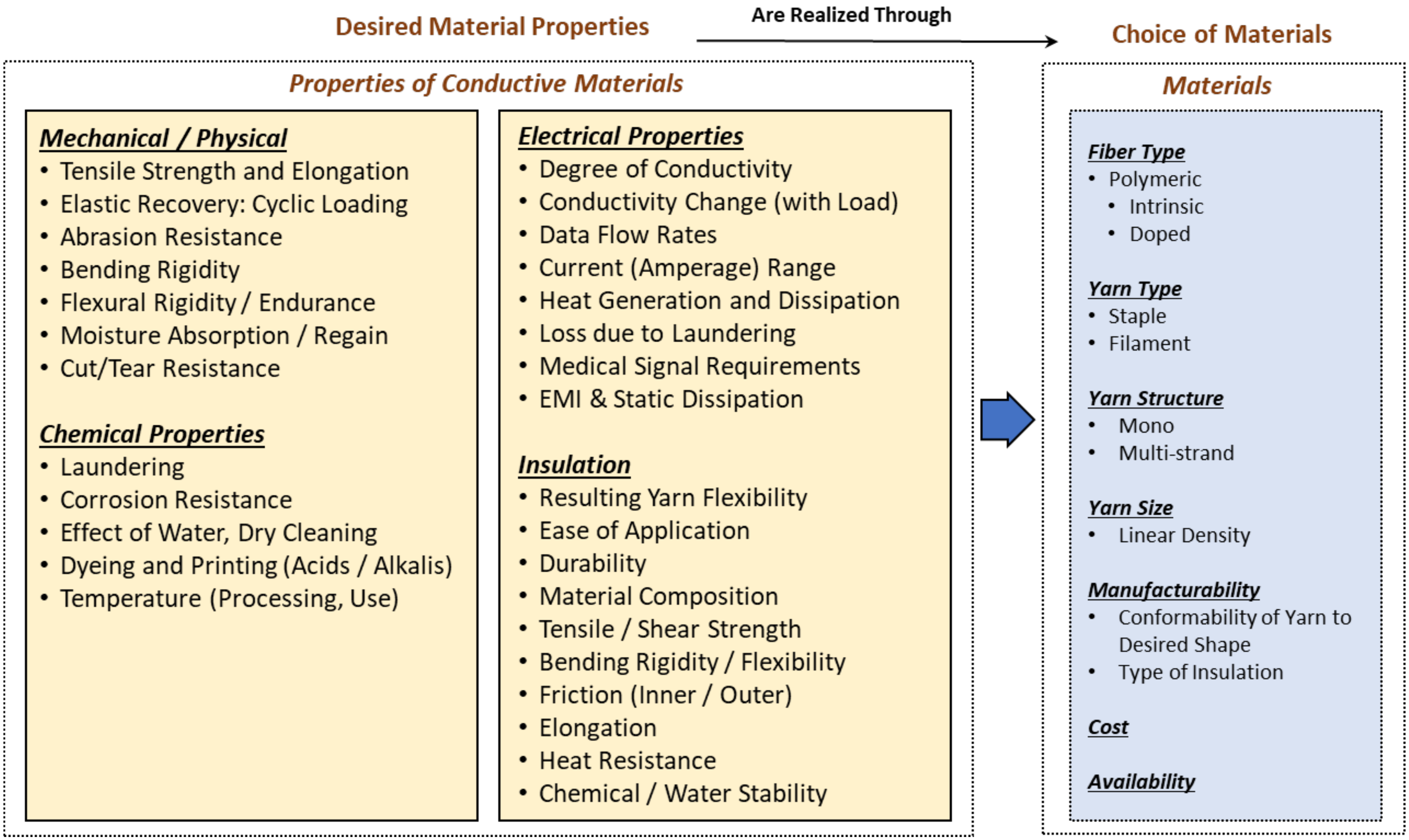

Figure 5-1 A Framework for Selection of Conductive Fibers for Sensate Liner

They include Mechanical/Physical, Chemical, Electrical and Insulation Properties, which are driven by the performance requirements of the structure. In turn, these desired material properties are realized through the proper selection of fibers based on the fiber and yarn types, manufacturability, cost and availability, among others. This approach to the analysis of conductive fibers as the information infrastructure component should help in two ways:

(i) Identify the desired properties in conductive materials and then design fibers (at the chemical and molecular levels) to meet those property requirements; and

(ii) Selection of conductive fibers for different applications of textile structures incorporating the information infrastructure component.

So, testing and evaluation of conductive fibers have been carried out in two forms (1) as yarns; and (2) as fabrics with woven-in conductive fibers.

5.2 Testing and Evaluation of Conductive Yarns

A series of experiments has been designed and carried out to test the effects of:

- yarn material type (all yarns with and without insulation);
- signal frequency (210Hz to 1010Hz);
- applied voltage (1.3V to 1.9V);
- type of deformation (Constant Rate of Loading, Constant Rate of Elongation); and
- tensile strain rate (0% to breaking strain)

on the electrical and tensile properties of conductive yarns as shown in Figures 5-2 and 5-3.

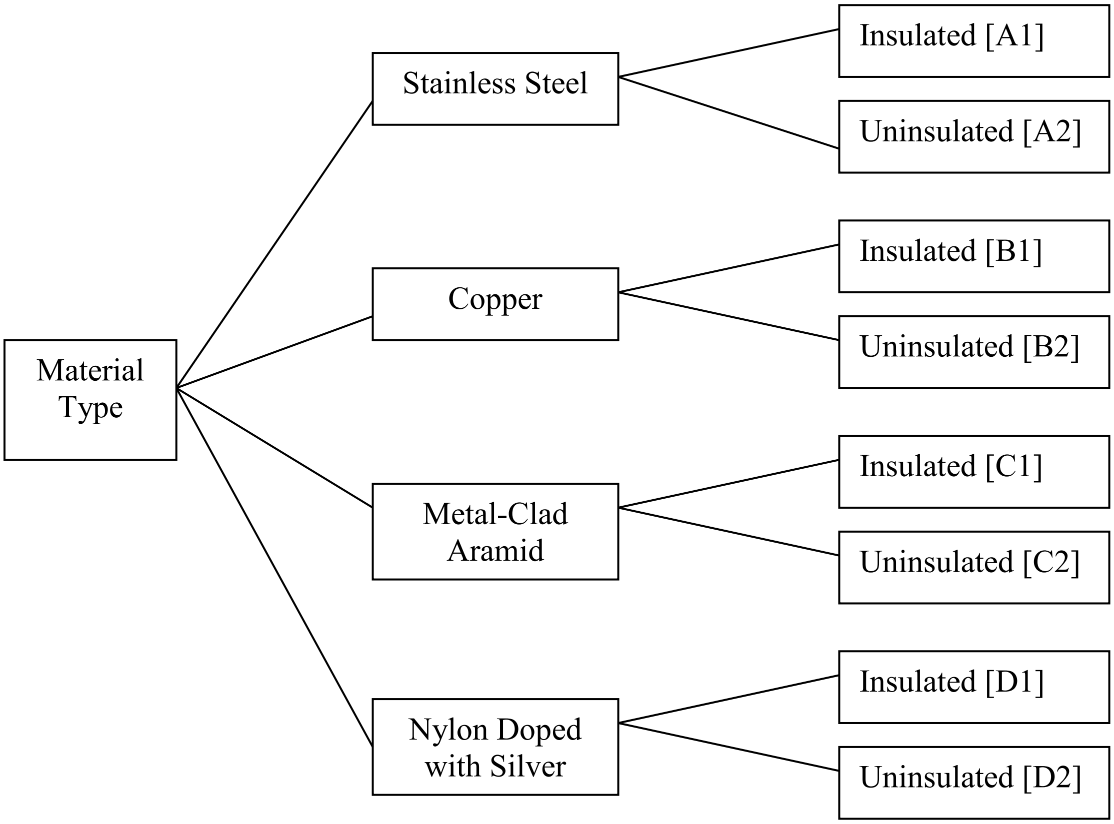

Figure 5-2 Spectrum of Material Types

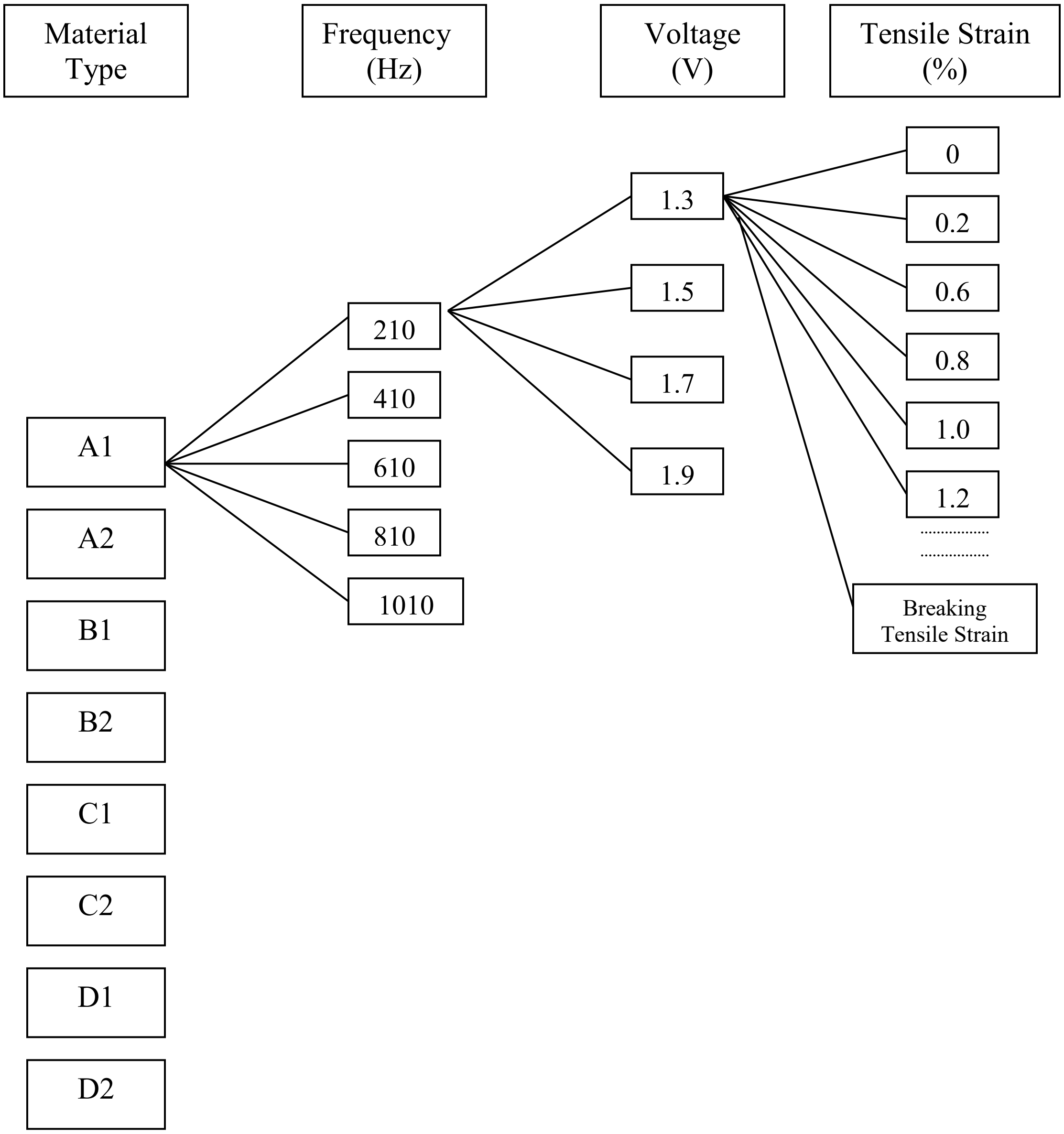

Figure 5-3 Test Specimens and Conditions

5.2.1 Test Methods

Tensile tests have been carried out using ASTM D-2256 Test Method on the Instron tester. Initially, both Constant Rate of Loading (CRL) and Constant Rate of Elongation (CRE) methods have been used. Since there was no difference in the results from the two methods, the CRE (10 mm/min) method was adopted for the study. As per the ASTM standard, three tests were carried out for each test sample with a gauge length of 250 mm.

The following instruments were used in carrying out the tests:

- Instron 5567 Tensile Tester
- HP Multimeter (HP 34401A)
- HP Function Generator (HP 33120A)
- Oscilloscope (HP 54615B)
- VEE Software System

5.2.2 Testing Set-up for Electrical Properties

Figure 5-4 shows the schematic of the initial set-up used in the study of the electrical properties of the yarns. As shown in the figure, a function generator, an external resistor and the candidate yarn were connected in series. An oscilloscope was connected to assess the role of inductance and capacitance of the test yarn. There was no phase delay between the two probes of the oscilloscope indicating that there was no effect of inductance or capacitance on the yarn. Therefore, the test yarns were considered to be pure resistors.

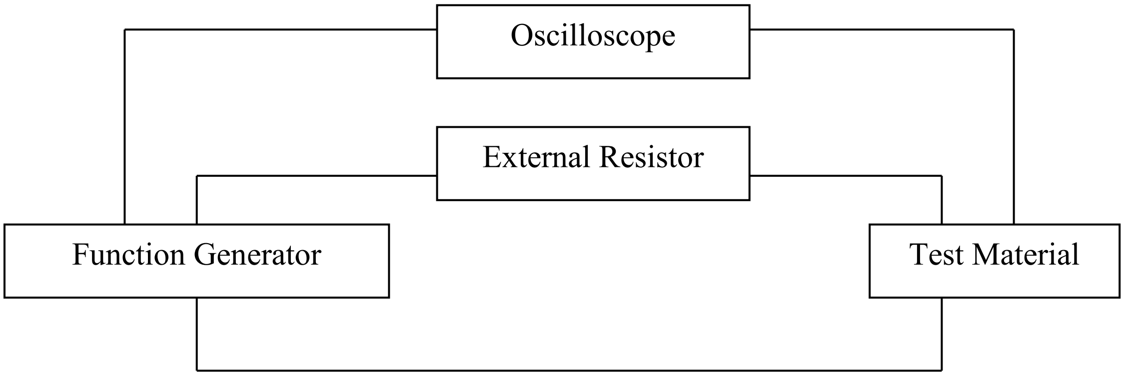

Figure 5-4 Schematic Drawing of Inductance and Capacitance Testing

Figure 5-5 shows the schematic of the final set-up used in assessing the electrical properties of the yarns. The internal resistance of the multimeter has an important effect on the measurements at low currents and frequencies. Therefore, an external resistor similar in value to the resistance of the yarn is used to minimize the errors due to such internal resistance of the instrument.

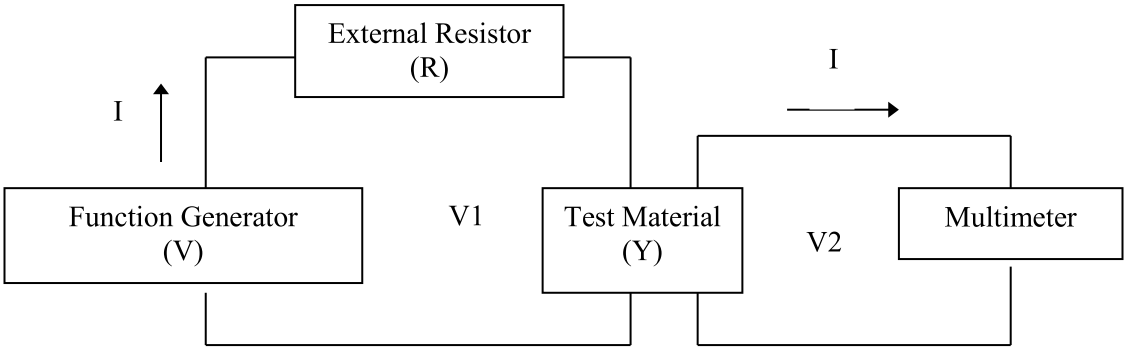

Figure 5-5 The Test Set-up for Electrical Properties of Yarns and Fabrics

Figure 5-6 shows the experimental set-up for testing the effect of tensile strain on the electrical properties of conductive yarns and fabrics with woven-in conductive fibers.

Figure 5-6 Effect of Tensile Strain on Electrical Properties: Overview of Set-up

Figure 5-7 shows the test sample mounted on the Instron tester; its ends are connected to the electrical instruments depicted earlier in Figure 5-5.

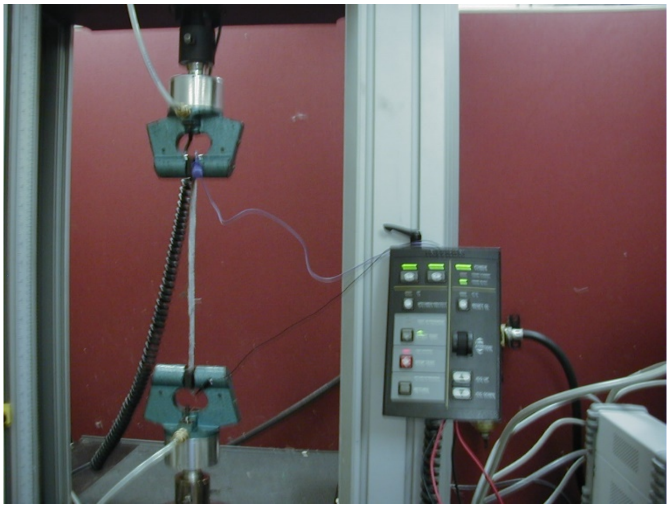

Figure 5-7 Test Sample mounted on the Instron Tester

5.2.3 Results and Discussion

The test results and detailed analysis for each material and processing condition are included in Appendix I. Table 5-1 is a partial summary of the effect of tensile strength on the conductive yarns. The values represent the average of three test specimens per sample.

Table 5-1 Summary of Conductive Yarn Test Results

Material[1]	Linear Density	Resistance at 0%	Resistance at Break[2, 3]	Breaking Tensile Strain	Breaking Load	Tenacity
	Tex (Ne)	Ohm	Ohm	%	Kgf	g/tex
A1	256 (2.3)	17.70	17.8	1.23	2.14	8.36
A2	107 (6)	22.14	24.9	1.27	2.04	19.07
B1	724 (0.8)	0.26	0.28	9.8	1.67	2.31
B2	448 (1.3)	0.27	0.33	29.93	1.3	2.90
C1	416 (1.4)	0.84	0.85	2.16	6.73	16.18
C2	144 (4)	1.3	1.42	2.79	3.44	23.89
D1	137 (4)	88.89	593.69	19.13	1.53	11.17
D2	40 (15)	60.66	982.66	30.57	0.89	22.25

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[1] See Figure 3.5.2 for descriptions of material types.

[2] The resistance of the material is calculated using Ohm's Law and the set of equations based on the circuit in Figure 3.5.5:

$V_1=I*(R+Y)$
$V_2=I*Y$
$V_1 / V_2 = I * (R+Y) / I * Y$

Therefore, $Y = RV_2 / (V_1-V_2)$

Where
V_1: The voltage from Function Generator
V_2: The voltage measure on the multimeter
R: The external resistor
Y: The resistance of the yarn
I: The current in the circuit

[3] The value of Resistance at Break of each material is measured at 1010 Hz and 1.9 V.

Table 5-2 shows a diagrammatic representation of the effects of tensile strain, frequency and voltage on the electrical resistance of insulated and uninsulated conductive yarns tested.

Table 5-2 Diagrammatic Representation of Electrical Properties of Conductive Yarns

Material Type		Effect of		
		Tensile Strain	Frequency	Voltage
		On Resistance of Yarns		
Stainless Steel	Insulated	↔	↔	↔
	Uninsulated	↑	↔	↔
Copper	Insulated	↔	↔	↔
	Uninsulated	↔	↔	↔
Metal Clad Aramid	Insulated	↔	↔	↔
	Uninsulated	↑	↔	↔
Nylon doped with Silver	Insulated	↑↑	↔	↔
	Uninsulated	↑↑	↔	↔

<u>Notation:</u>

↔	↑	↑↑
No Change	Increase	Significant Increase

5.2.3.1 Effect of Yarn Structure on the Resistance of Materials

Stainless steel, metal-clad Aramid and Nylon doped with silver yarn are multifilament yarns while the copper wire[4] has a "solid" structure. This difference in the basic structure is reflected in the response of the insulated and uninsulated yarns in the two classes to tensile deformation, and hence resistance (as seen in Table 5-2): The resistance of the uninsulated stainless steel, Aramid and Nylon-doped fibers increases with tensile strain while that of the uninsulated copper wire remains the same with increase in tensile strain.

5.2.3.2 Effect of Insulation on Tensile Properties of all Materials

As seen in Table 5-1, the tenacity of the uninsulated yarn is higher than that of the insulated yarn. This difference in strength between the two yarns – for all materials – can be attributed to the "composite" nature of the insulated yarn and the resulting differences in the response to tensile deformation.

5.3 Testing and Evaluation of Fabrics with Woven-in Conductive Fibers

It is important to assess the performance of the information infrastructure component when it has been integrated into the fabric. Such an assessment will provide an indication of the behavior of the material when the Sensate Liner is worn and used by the soldier. Therefore, the yarns listed in Figure 5-2 have been woven into a set of fabrics, which have then been used in a series of experiments to test the effects of:

- conductive yarn material type (all yarns with and without insulation);

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[4] Unlike the other yarns including stainless steel, copper is not in fiber form.

- signal frequency (210 Hz to 1010 Hz);
- applied voltage (1.3 V to 1.9 V);
- type of deformation (Constant Rate of Loading, Constant Rate of Elongation); and
- tensile strain rate (0 % to breaking strain)

on the electrical and tensile properties of the fabrics.

5.3.1 Test Methods

The same test methods used earlier for yarns (Section 5.2.1) have been used to test the conductive yarns woven into fabrics.

5.3.2 Specifications of Fabric Test Samples

Table 5-3 shows the specifications of the fabric test samples.

Table 5-3 Specifications of Fabric Test Samples

Sample Size	300mm x 15 mm
Warp	18s Ne, 100% Cotton
Filling	30s Ne, Core-spun Spandex for base and conductive yarns listed in Figure 3.5.2
Structure	Plain Weave
Ends/inch	24
Picks/inch	24 base yarns + 1 conductive yarn

5.3.3 Test Set-up for Electrical Properties

The same testing set-up used earlier for yarns (Section 5.2.1) has been used for testing the fabrics.

5.3.4 Results and Discussion

The test results and detailed analysis for each material and processing condition are included in Appendix I. Table 5-4 is a partial summary of the effect of tensile strength on the conductive yarns woven into fabrics. The values represent the average of three test specimens per sample.

Table 5-4 Summary of Test Results

Material[5]	Resistance at 0%	Resistance at Break[6,7]	Breaking Tensile Strain	Breaking Load
	Ohm	Ohm	%	Kgf
A1	20.66	21.18	14.54	2.34
A2	20.57	20.92	17.01	0.53
B1	0.22	0.23	11.33	1.66
B2	0.28	0.30	24.9	4.27
C1	0.77	0.91	4.0	6.15
C2	1.28	1.44	20.0	4.76
D1	88.61	469.01	29.8	3.23
D2	60.96	507.9	48.09	3.25

---

[5] See Figure 3.5.2 for material types.

[6] The resistance of the material is calculated using Ohm's Law and the set of equations based on the circuit in Figure 3.5.5:

$V_1=I*(R+Y)$
$V_2=I*Y$
$V_1 / V_2 = I * (R+Y) / I * Y$

Therefore, $Y = RV_2 / (V_1-V_2)$

Where
V_1: The voltage from Function Generator
V_2: The voltage measure on the Multimeter
R: The external resistor
Y: The resistance of the yarn
I: The current in the circuit

[7] The value of Resistance at Break of each material is measured at 1010 Hz and 1.9v.

Table 5-5 shows a diagrammatic representation of the effects of tensile strain, frequency and voltage on the electrical resistance of insulated and uninsulated) fabrics with woven-in conductive fibers

Table 5-5 Diagrammatic Representation of Electrical Properties of Fabrics with Woven-in Conductive Fibers

Material Type		Effect of		
		Tensile Strain	Frequency	Voltage
		On Resistance of Yarns		
Stainless Steel	Insulated	↑	↔	↔
	Uninsulated	↑	↔	↔
Copper	Insulated	↔	↔	↔
	Uninsulated	↔	↔	↔
Metal Clad Aramid	Insulated	↑	↔	↔
	Uninsulated	↑	↔	↔
Nylon doped with Silver	Insulated	↑↑	↔	↔
	Uninsulated	↑↑	↔	↔

Notation:

↔	↑	↑↑
No Change	Increase	Significant Increase

5.3.4.1 Effect of Tensile Strain on Fabrics with woven-in conductive fibers

As shown in Table 5-5, the resistance of different conductive yarns woven into fabric (except Copper yarn) increases with increases in tensile strain. However, the variation of electrical resistance of the yarns starts to increase when the tensile strain of the yarn is close to its breaking strain. There is no effect of tensile strain on the conductive yarns during the initial stages of tensile strain. Unlike the other conductive yarns, the Nylon doped with silver yarn stretches right from the beginning of tensile strain. This is because Nylon is highly extensible (25%-30% breaking strain) and the conductive yarn begins to stretch as soon as the base fabric is subjected to stretch. In other cases, the base fabric stretches before the conductive yarn in the woven fabric because the base fabric has higher elongation than the conductive yarn.

5.3.4.2 Effect of Frequency and Applied Voltage on Fabrics with woven-in conductive fibers

As shown in Table 5-5, there is no significant effect of frequency and voltage on all tested conductive yarns woven into fabric at any given tensile strain. This behavior is similar to that of the conductive yarns tested in yarn form.

5.4 Research Outcome

This facet of the research has led to an understanding of the potential of conductive yarns to serve as an information infrastructure component for the Sensate Liner. The investigations have also enabled the selection of conductive fibers for the Sensate Liner.

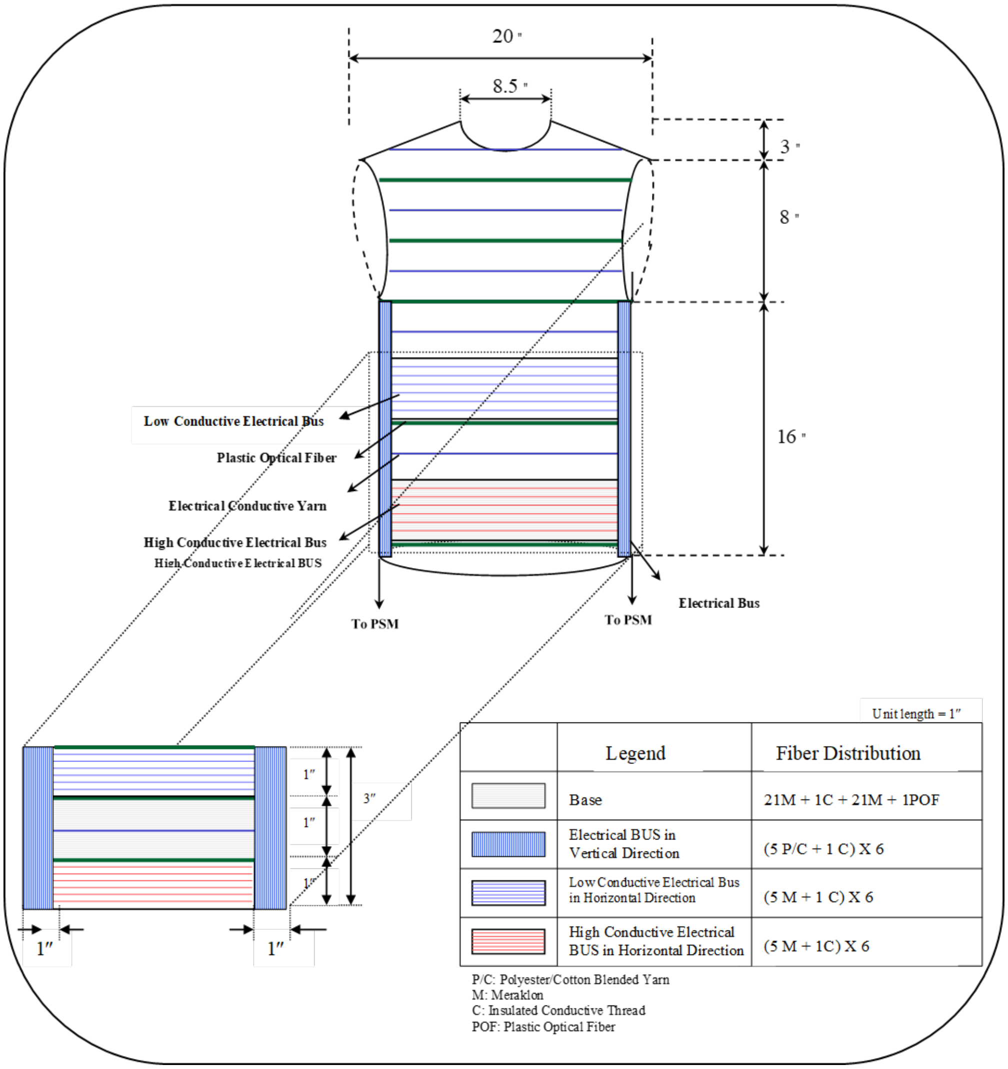
CHAPTER 6

Realization of the Wearable Motherboard

In this Chapter, we discuss the integration of the various building blocks presented earlier to create the woven Sensate Liner for combat casualty care. We discuss the successful demonstration of the penetration sensing and monitoring capabilities of the Sensate Liner. Since undergarments are typically made from knitted fabrics, we investigate the development of a knitted version of the Sensate Liner. The details of the launderability tests carried out in collaboration with a major consumer goods manufacturer are presented. Finally, we present the concept of a Wearable Motherboard to represent the new paradigm of “fabric as an information infrastructure” or “fabric is the computer,” through specific instantiations of the technology for a host of potential applications.

6.1 Design and Fabrication of the Third Generation Woven Sensate Liner

The overall design of the third generation Sensate Liner is shown in Figure 6-1.



	Legend	Fiber Distribution
▭	Base	21M + 1C + 21M + 1POF
▥	Electrical BUS in Vertical Direction	(5 P/C + 1 C) X 6
▤	Low Conductive Electrical Bus in Horizontal Direction	(5 M + 1 C) X 6
▤	High Conductive Electrical BUS in Horizontal Direction	(5 M + 1C) X 6

P/C: Polyester/Cotton Blended Yarn
M: Meraklon
C: Insulated Conductive Thread
POF: Plastic Optical Fiber

Figure 6-1 Design Specifications of Third Generation Woven Sensate Liner

The structure has been produced using 100% core-spun spandex and Meraklon for filling and 100% polyester/cotton for warp. The ends of the sheathed POF were sealed to ensure that the POF stayed in place during use. The sealing also prevents air, water, and external fluids from entering the protective jacket and damaging the bare POF. As mentioned in Section 3.3, two separate POFs – one for the top and another for the bottom layer of the fabric – have been used to minimize the sharp bending of the POF. A 280 denier spandex has been used in the armhole region since the 280 denier core-spun spandex has a lower stretch than the 560 denier core-spun spandex and the armhole region does not require a high degree of form-fitting. Thus, the design parameters can be varied depending on the desired end-use application and performance characteristics in the resulting Sensate Liner. Table 6.1 shows the specifications for a variety of Sensate Liners with different performance characteristics.

Table 6.1 Specifications of Woven Sensate Liner

Unit Area: 1inch^2

Degree of Form-Fitting	Fabric Width	Ends / Inch		Picks / Inch				Electrical Bus			
		P/C	C	M	S	C	POF	Horizontal Direction		Vertical Direction	
								M	C	P/C	C
0%	24″	35	1	42	0	1	1	30	6	30	6
50%	21″	35	1	21	21	1	1	30	6	30	6
100%	19″	35	1	0	42	1	1	30	6	30	6

P/C: Polyester/Cotton Blend Yarn
M: Meraklon
S: Core-Spun 560 denier Spandex with Polyester and Cotton blended
C: Insulated Conductive Thread

6.1.1 The Plug and Play Modular Design: The Concept of T-Connector

There is the need for an effective way to connect the sensors on the soldier's body (e.g., heart rate, temperature) and other devices (e.g., microphone) to the Sensate Liner during use and remove them before laundering. To facilitate this capability, inspiration was drawn from button clips used in clothing and this led to the concept of a "T-

Connector" – a receptacle that could be integrated into the fabric at the desired interconnection point into which the sensor heads could be plugged (see Figure 6-2). By modularizing the design of the fabric (using the T-Connectors), the sensors themselves can be made independent of the fabric. This accommodates different body shapes. The T-Connector makes it relatively easy to attach the sensors to the integrated information component or conductive fibers in the Sensate Liner. Thus, this innovative and modular design enhances the versatility and usability of the Sensate Liner including facilitating its launderability.

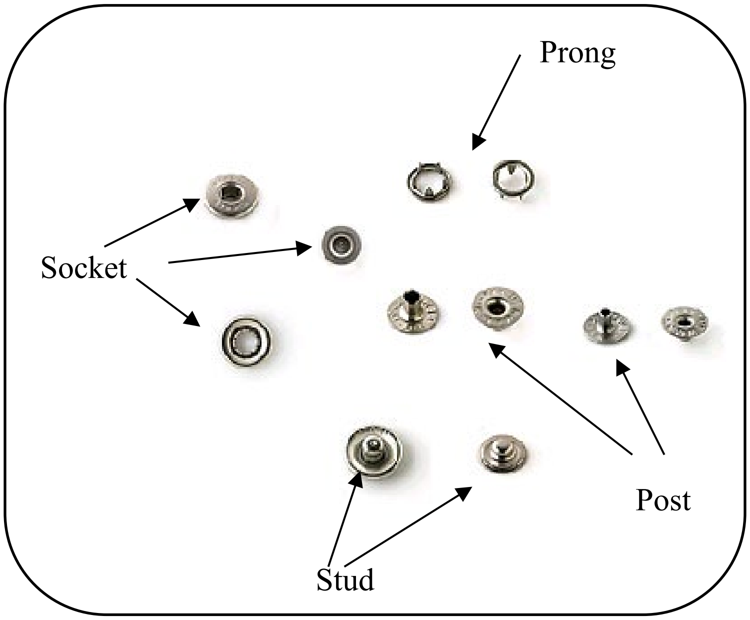


Figure 6-2 Sample of T-Connectors Evaluated for Use in Prototype

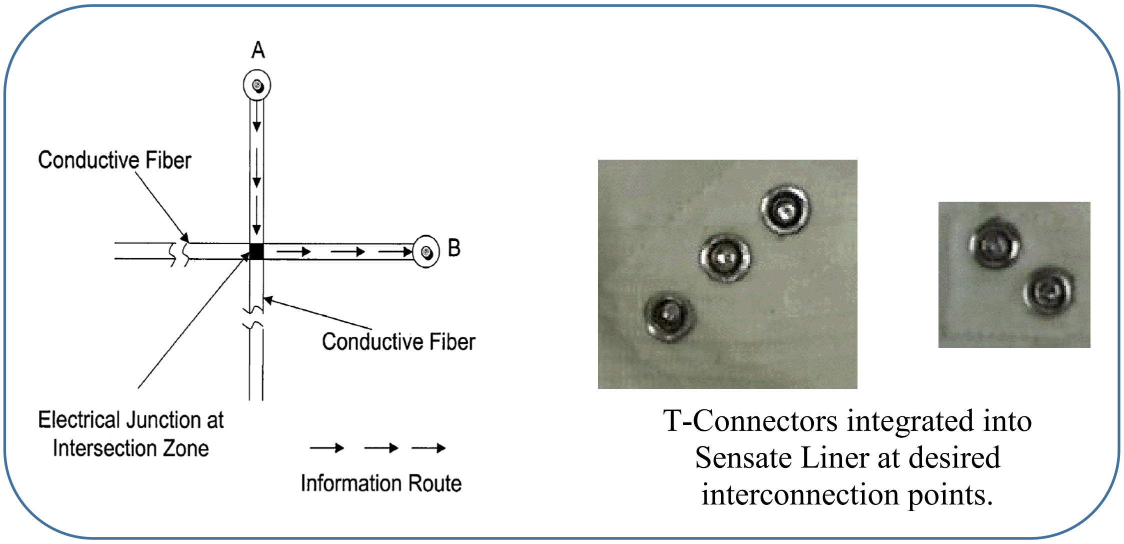
6.1.1.1 Integrating the T-Connectors into the Sensate Liner

Table 6-2 gives the details of the T-Connectors evaluated for use in the Sensate Liner. These were obtained from Universal Fasteners. During the interconnection process (discussed in Chapter 4), the T-Connector is placed at the desired interconnection point after the conductive paste has been applied. The tightness of the "sensor head" in the T-Connector has been used as a measure in arriving at the desired T-Connector because the relative motion can lead to artifacts in the signals. In addition, the ease of application has been used as the other key criterion in selecting the T-Connector. Based on the results of the testing, the first three in the Table performed equally well.

Table 6-2 Details of T-Connectors Used

Item #	Item
4910000310	16/ OPR Brass Nickel LL
4870000310	16/ Brass Socket Nickel
4850000310	16/ Brass W Stud Nickel
X650000310	15/ OPR Brass Nickel LL
X620000310	15/ Brass Socket Nickel
X630000310	15/ Brass W Stud Nickel

Figure 6-3 shows a schematic of the routing of information between two T-Connectors (A and B) in the fabric along with examples of T-Connectors integrated at the interconnection points.

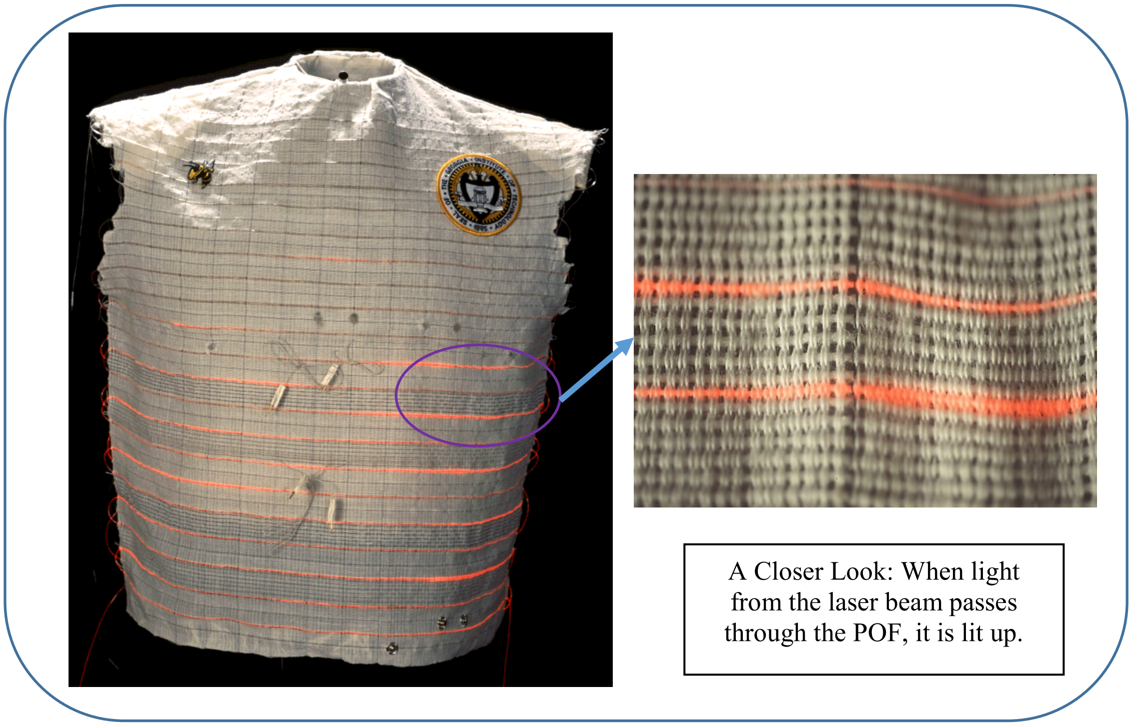


T-Connectors integrated into Sensate Liner at desired interconnection points.

Figure 6-3 Information Routing between T-Connectors through the Interconnection Point

6.1.2 The Integrated Woven Sensate Liner

Figure 6-4 shows the third generation Sensate Liner after the interconnections have been made and the T-Connectors have been incorporated. A closer look at the fabric shows the light passing through the POF integrated into the structure. The final specifications for the Sensate Liner are shown in Table 6-3.



A Closer Look: When light from the laser beam passes through the POF, it is lit up.

Figure 6-4 The Third Generation Sensate Liner

Table 6-3 Final Specifications of the Third Generation Sensate Liner

Component	**Materials**	**Count**
Penetration Sensing (PSC)	Plastic Optical Fibers (POF)	12s Ne POF (sheathed)
Comfort (CC)	Meraklon Microdenier Poly/Cotton Blend Spandex	8s Ne
Form-fitting (FFC)	Spandex	8s Ne Core-Spun Spandex
Global and Random Conducting (ECC)	• Copper with polyethylene sheath • Doped inorganic fiber with sheath	6s Ne
Static Dissipating (SDC)	Nega-Stat	18s Ne

6.2 Testing and Evaluation of Woven Sensate Liner

To demonstrate the successful realization of the twin capabilities of the Sensate Liner, viz., detecting the penetration of a projectile and monitoring the soldier's vital signs, tests have been carried out.

6.2.1 Penetration Alert Testing

The bench-top set-up to test the penetration sensing capabilities of the Sensate Liner is shown in Figure 6-5. When the POF is intact, the light from the laser at the bottom of the Sensate Liner travels through the POF in the Sensate Liner. At the other end of the POF, a photo-diode connected to a power-measuring device measures the power output from the POF.

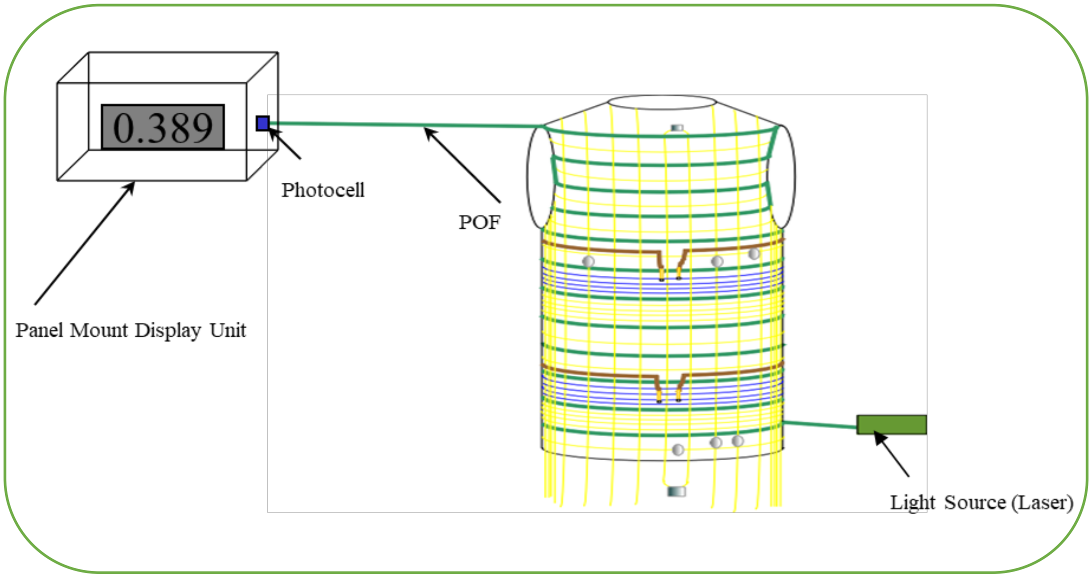


Figure 6-5 Benchtop Testing Set-up for Penetration Alert Sensing

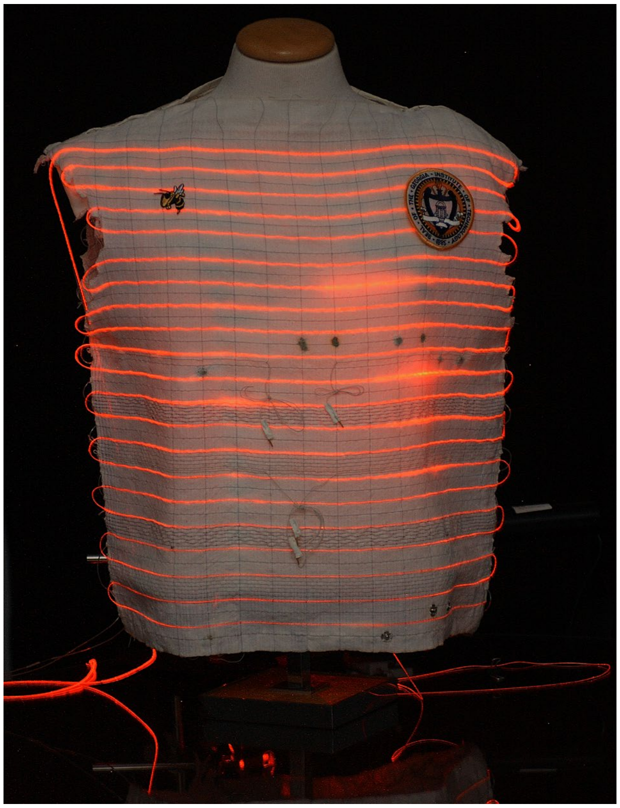


Figure 6-6 The Sensate Liner is “Armed” for Projectile Penetration Testing

Figure 6-6 shows the POF completely “lit up” at the start of the test indicating that the Sensate Liner is armed and ready to detect projectile penetration. The intensity of the light is measured at the top as shown in the display in Figure 6-5. Projectile penetration is simulated by cutting the POF in the structure with a pair of scissors. When the POF is cut, the power output at the other end on the measuring device fell to zero, thus demonstrating the proper functioning of the Sensate Liner to detect penetration. To identify the exact point of break, i.e., projectile penetration in the Sensate Liner, an Optical Time Domain Reflectometer[1] connected to the POF can be used.

6.2.2 Vital Signs Monitoring

To monitor the heart rate, three electrocardiogram (EKG) sensors similar to the ones used in hospitals are attached to the human subject's torso; the subject donned the Sensate Liner (like wearing any undershirt) and used the T-connectors to snap into the EKG sensors on the body (See Figure 6-7).

Figure 6-7 Sensate Liner on a Subject

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[1] An Optical Time Domain Reflectometer (OTDR) is used to detect the precise location of faults in an optical fiber link of a communication network. This technique is recommended to detect the exact location of projectile penetration in the Sensate Liner.

Initial testing was carried out at Crawford Long Hospital followed by extensive set of tests in the Department of Physiology at Emory University. The EKG trace from one of the tests at Emory University is shown in Figure 6-8. A physician reviewing the data from the Sensate Liner and directly from the body (the control) concluded that the waveforms and heart rate data were identical and confirmed the vital signs monitoring functionality of the Sensate Liner. Similarly, the subject’s temperature was monitored using a thermistor-type sensor. A subject wearing the Sensate Liner continuously for long periods of time evaluated the garment's comfort. The subject's behavior was observed to detect any discomfort and none was detected. The garment was also found to be easy to wear and take-off. Thus, these tests conclusively demonstrated the realization of the desired twin functionalities in the Sensate Liner.

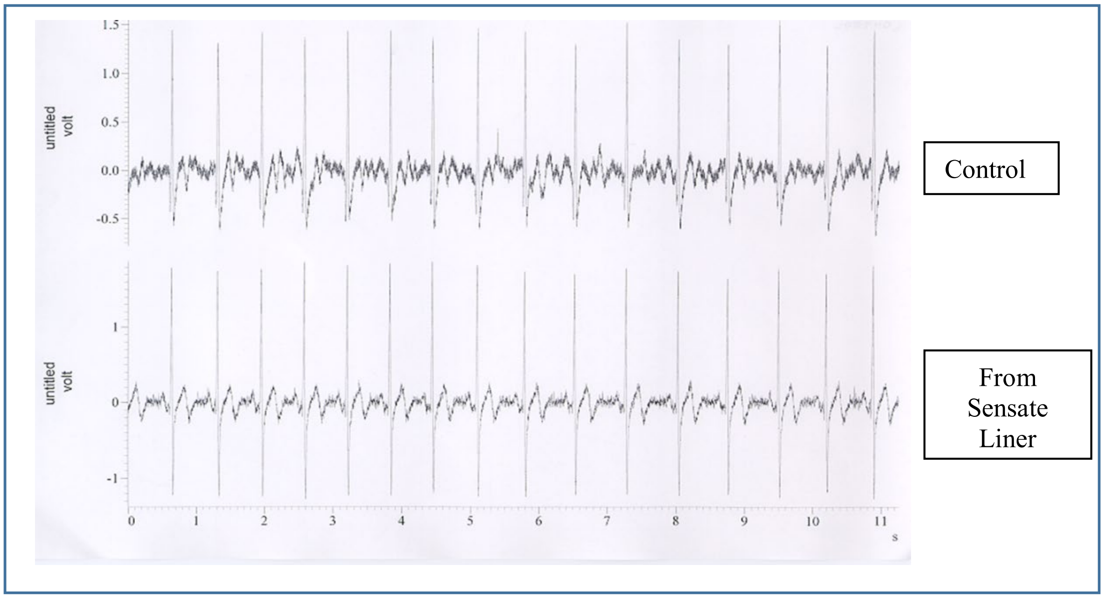

Figure 6-8 EKG Trace from Subject – Control and From the Sensate Liner

6.2.3 Hand Laundering Test

The Sensate Liner has been subjected to hand laundering. There were no significant differences in the attenuation of the POF and conductivity of the conductive thread in the Sensate Liner before and after hand wash. This hand laundering test demonstrates the launderability of Sensate Liner. Details of the extensive set of tests to assess the repeated launderability are presented in Section 6.4.

6.3 Design and Fabrication of a Knitted Sensate Liner

Undergarments are typically made of knitted fabrics as they provide better form-fit than woven fabrics. Since the feasibility of the concept of a fabric-based Sensate Liner had been successfully proven, research has been directed at creating a knitted version of the Sensate Liner. This investigation also illustrates the value of the design and development framework proposed earlier and validated for the woven version of the Sensate Liner.

6.3.1 Structure and Realization of First Generation Knitted Sensate Liner

A semi-automatic flat-bed knitting machine has been used to create the knitted version of the Sensate Liner. Figure 6-9 shows the structure of the garment in which one single POF is continuously inlaid throughout the structure. The conductive yarn is also inlaid in the structure. The comfort component, Meraklon, forms the 1x1 rib structure and serves as the base of the fabric. The electrical bus (conductive fiber) in the structure is also shown in the figure. In this first version of the knitted Sensate Liner, the electrical bus has been knitted separately and attached to the structure at the sides. Since the feasibility of using POF to detect projectile penetration had been successfully proven with the woven version, it was decided to use the commercially-available "jacketed" version of POF in the knitted Sensate Liner. The properties of the two versions of the jacketed POF provided by Toray Industries are shown in Table 6-4. Since PGU-CD-501-10-E has a lower allowable bending radius compared to the PFU version, it has been used to produce the Sensate Liner as it would minimize signal attenuation when bent in the garment.

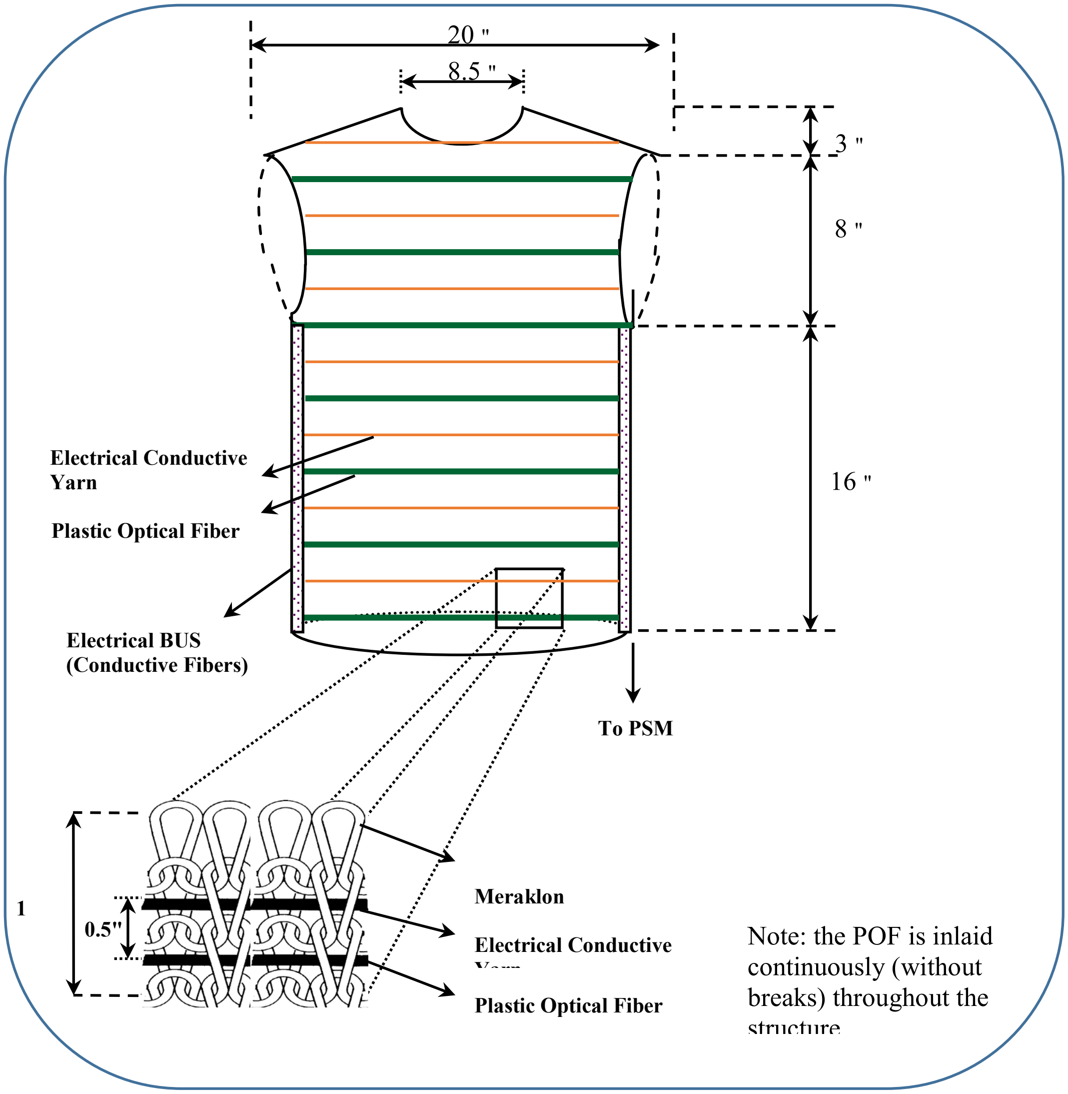

Figure 6-9 Design of the Knitted Version of the Sensate Liner

Table 6-4 Physical Properties of Jacketed POF

Parameter	PFU-CD 501-10-E	PGU-CD 501-10-E
Material of Core	Polymethyl methacrylate	Polymethyl methacrylate
Material of Cladding	Fluorinated Polymer	Fluorinated Polymer
Diameter (Fiber)	0.5 mm	0.5 mm
Jacket Diameter	1.0 mm	1.0 mm
Allowable Bending Radius	> 17 mm	> 9 mm
Temperature Range for Use	- 40 to 85^{o}c	-40 to 70^{o}c

Table 6-5 shows the materials used to produce the first generation knitted Sensate Liner.

Table 6-5 Materials Used in the First Generation Knitted Sensate Liner

Fiber/Yarn	**Description**
Plastic Optical Fiber	PGU-CD-501-10-E from Toray Industries, Japan
Electrical Conductive Fiber	X-Static Conducting Nylon fiber with insulated PVC Sheath from Sauquoit Industries, Pennsylvania
Meraklon	Yarn from Dawtex, Inc., Canada

The front view of the knitted Sensate Liner is shown in Figure 6.10. The necessary interconnections were made and T-Connectors incorporated into the structure. Both the penetration sensing and vital signs monitoring capabilities of the knitted version have been successfully tested.

Figure 6-10 Front View of First Generation Knitted Sensate Liner

6.3.2 Enhancing the Usability: Velcro and Zipper Attachments

In combat situations, the Sensate Liner may have to be taken off easily and quickly from the injured soldier to render proper medical aid. Likewise, in medical situations, a patient may not be physically capable of putting on the Sensate Liner in a manner similar to an undershirt, i.e., over the head. To facilitate the ease of donning and doffing, velcro and zipper attachments have been used to integrate the front and back of the knitted Sensate Liner as shown in Figures 6-11. The user can easily and simply wrap the structure around the body and use the closure to create a form-fitting garment that can monitor the vital signs and, in the case of the soldier, detect project penetration as well.

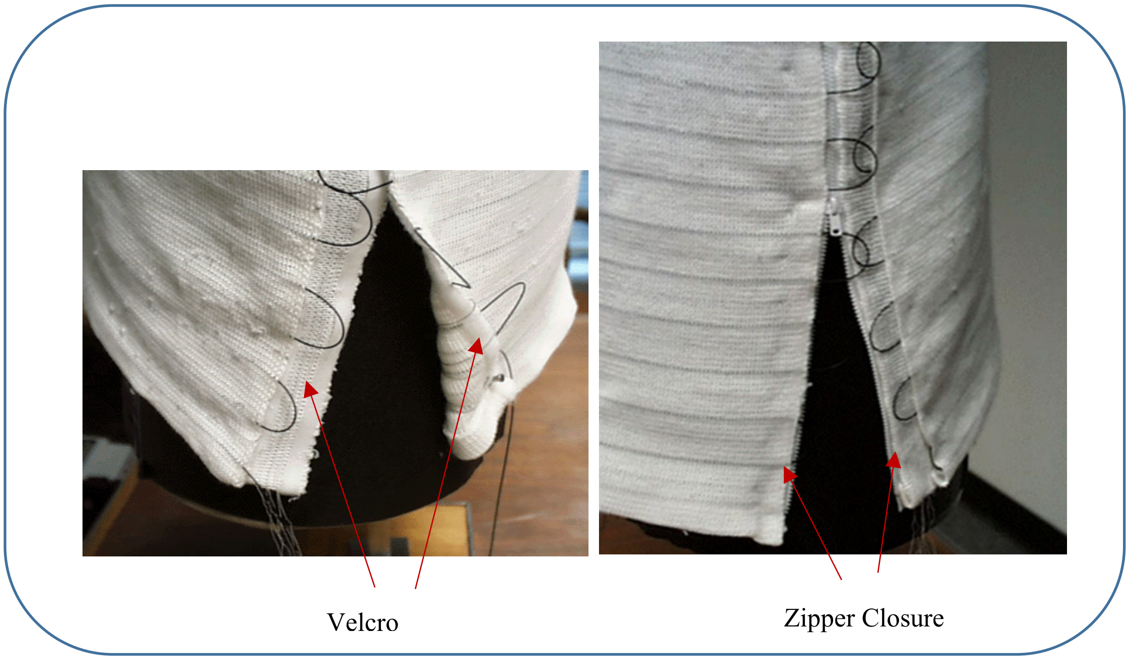

Figure 6-11 Enhancing the Usability: Velcro and Zipper Closures in Knitted Sensate Liner

6.4 Evaluation of the Launderability of Sensate Liners

The failure of any product in use will impair its usefulness or value. This is even more critical in the case of the Sensate Liner, which is designed as a technology to save lives in the battlefield. Failure Modes and Effects Analysis (FMEA) is a methodology used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures [53].

The following modes of failure of the Sensate Liner have been identified as part of a high-level FMEA:

- Failure due to Interconnections
- Failure due to T-Connectors
- Failure due to Breaks/Cuts in the Fabric/Garment

- Failure due to Improper Positioning of the Sensors on the User
- Failure due to Improper Positioning of the Sensors in the T-Connector
- Failure due to Laundering
- Failure due to End of Product Life-Cycle
- Failure due to Data Loss in Wireless Transmission
- Failure due to Improper Use of the Technology

We now discuss the results of the work carried out to assess the potential failure of the technology due to laundering.

6.4.1 Launderability Testing: The Experimental Plan

The launderability of the Sensate Liner has been evaluated in collaboration with a major consumer goods manufacturer[2]. The twin objectives of the test were to assess the impact of laundering on the functional performance and appearance of a version of the Sensate Liner without the plastic optical fiber and the effect of stains on the cleaning of the fabric. In particular, the effects of laundering on conductive yarns, conductive paste/ink and interconnections have been assessed to refine the specifications and architecture of the Sensate Liner.

Two sets of experiments have been designed to accomplish the twin objectives. Table 6-6 shows the plan for the evaluation of launderability of the Sensate Liner. To begin with, eight samples (known as functional samples in the table) would be laundered, while one would remain unwashed as the control. At the end of the first cycle, one of the

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[2] The name of the company collaborating in the launderability testing is confidential pursuant to a confidentiality agreement between that company and Georgia Tech.

samples would be replaced by a “non-functional sample” to maintain the other experimental conditions. Likewise, one sample each would be replaced at the end of five and ten cycles, respectively, with non-functional samples. The total number of cycles is 20. Tide® is the detergent used in the tests. Table 6-7 shows the plan for the cleaning/stain test of the Sensate Liner.

Table 6-6 Experimental Design for Launderability Testing

Sample Specification
o 9 functional samples (includes one non-washed)
o 7 non-functional samples (includes one non-washed)
Laundering Method
o Multi-cycle Testing (total 20 wash/dry cycles)
o 1, 5, 10, 20 cycles
o Detergent: Tide® Powder

Table 6-7 Experimental Design for Cleaning/Stain

Sample Specification
o Quantity: 10
o Size: 10 inch X 10 inch
Test Method
o Detergent: Tide® Powder
o Stains: up to 9 identical stains per swatches (i.e., baby food, blood, etc.)

6.4.2 Design and Production of Test Samples

The conductive fiber in the fabric and the interconnections are likely to be affected by laundering. Therefore, the use of two different types of conductive fibers in the fabric has been investigated. These were Nylon doped with silver from Saquoit and metallic fiber yarns from Bekaert. In addition, interconnections made with a conductive paste (Magnobond 3870) and with a conductive ink (Colortronics TXFS-007), respectively, have been investigated.

6.4.2.1 The Architecture for Launderability Test Samples

In creating the test samples for launderability, it was important to have as many conductive yarns, interconnections and T-Connectors as possible in each Sensate Liner so that the number of individual yarns/paths/connectors tested would be high. Therefore, the fabric samples have been architected to realize this objective. Figure 6-12 shows the design of the sample for the launderability test. The conductive yarns are spaced 0.7" apart as shown in the figure.

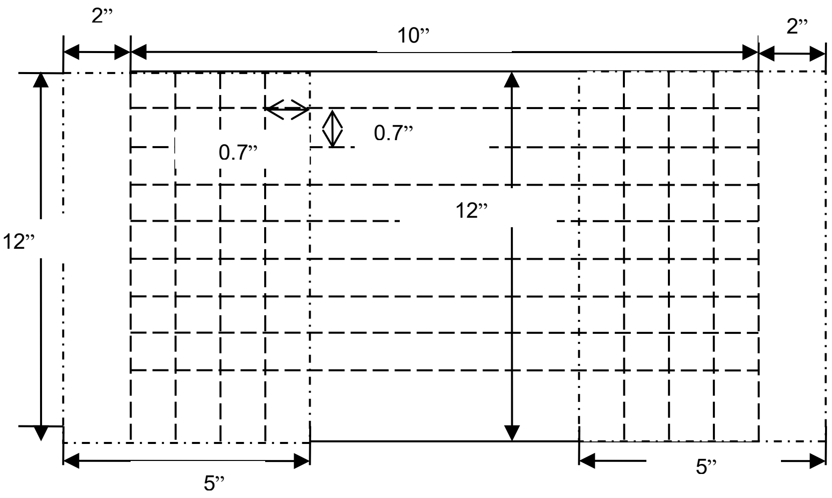


Figure 6-12 Architecture of Sensate Liner for Launderability Testing

6.4.2.2 Fabrication of Samples for Launderability Testing

Once the fabric samples were produced, multiple interconnections were made, T-Connectors were incorporated, and Sensate Liners were fabricated. Since the launderability test required 16 samples, a total of 32 samples was produced for the four variables. As shown in Figure 6-13, each sample had multiple interconnections and T-Connectors.

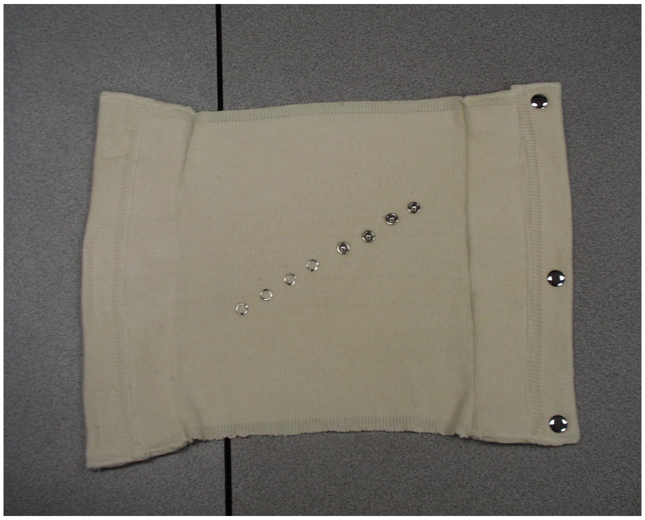


Figure 6-13 Sensate Liner Sample for Launderability Test

6.4.2.3 The Architecture for Cleaning/Stain Test Samples

In creating the test samples for the cleaning/stain tests, it was important to have as many conductive yarns, interconnections and T-Connectors as possible in each fabric swatch so that the number of individual yarns/paths/connectors tested would be high. Therefore, the fabric samples have been architected to realize this objective. Figure 6-14 shows the design of the sample for the cleaning/stain test. The conductive yarns are spaced 0.7” apart as shown in the figure.

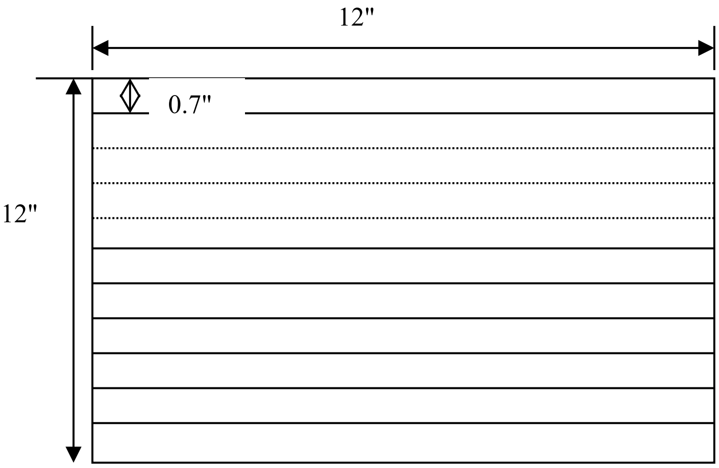


Figure 6-14 Architecture of Sample for Cleaning/Stain Test

6.4.2.4 Fabrication of Samples for Cleaning/Stain Testing

After the fabric samples were produced, multiple interconnections were made, and T-Connectors were incorporated into them. A total of 20 samples was produced for the four variables. As shown in Figure 6-15, each cleaning/stain test fabric sample had multiple interconnections and T-Connectors using the conductive paste and conductive ink.

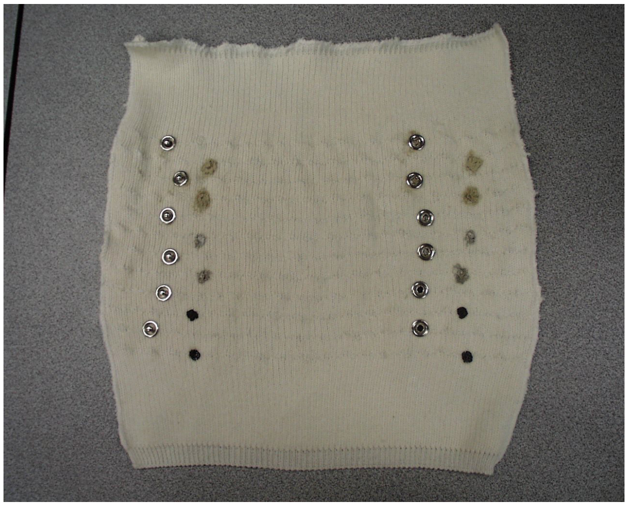


Figure 6-15 Sample for Cleaning/Stain Test

6.4.3 Testing

The fabricated test samples were sent to the collaborating company for testing (see Figure 6-16). The tests were conducted in accordance with the experimental plan presented in Section 6.4.1.1.

Figure 6-16 Snapshot of the Partial Set of Samples Sent to Collaborating Company

6.4.4 Evaluation and Analysis of Experimental Data

After the laundered samples were received from the collaborating company, they were visually inspected for damages and/or changes in appearance. There were no significant changes in the appearance of the samples. The interconnections and T-Connectors were also visually examined for any physical damage and none was found.

Conductivity measurements were carried out on all the samples. For each sample, the resistance along the various conducting paths was measured. Figure 6-17 shows a schematic representation of four conductive paths measured in the sample: 1-1’, 2-2’, 3-

3’ and 4-4’. It is important to note that the path lengths are not identical in the actual samples tested.

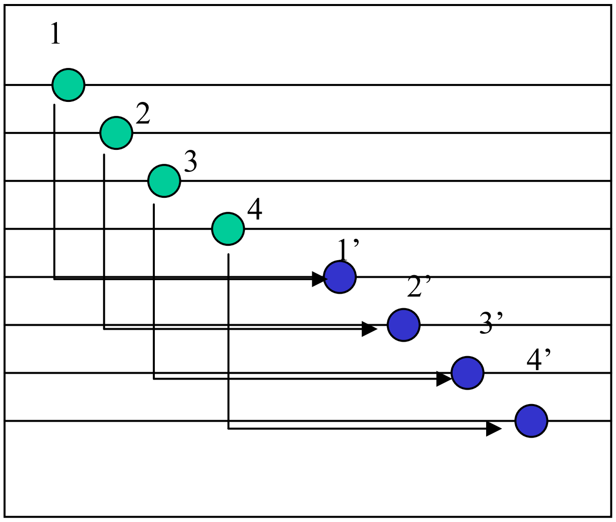


Figure 6-17 Resistance Measurements in Tested Samples
(Path lengths in the fabric are not equal)

Table 6-8 shows the results for stainless steel conductive yarns and Table 6-9 shows the results for the Nylon-doped with silver yarns. The variation in resistance values between the four paths in the sample is due to the different path lengths and the different conductive paste/ink used. In Figure 6-17, conductive ink was used for the interconnections at 1, 1’ and 2, 2’, while conductive paste was used at 3, 3’ and 4, 4’. As seen from the tables, the samples with Nylon-doped with silver yarns are affected more by laundering than the samples made from Stainless steel yarns. This finding helped in the selection of the Stainless steel yarn for the conductive yarn component in newer versions of the Sensate Liner. The conductive path along 3-3’ was literally non-existent at the end of the test on the Nylon-doped with silver sample (N/A in Table 6-9) further confirming the choice of the stainless steel fiber. For the samples with stainless steel yarns, conductive paste performed better than conductive ink (the latter probably got washed away during the test). The results of the laundering tests reinforced the selection of Magnabond 3870 (discussed earlier in Chapter 4) as the conductive paste for the interconnections.

Table 6-8 Resistance Values of Samples made from Stainless Steel Yarn

Unit: ohm

Path	0 cycle	1 cycle	5 cycles	10 cycles	20 cycles
1-1’	37	40	60	70	72
2-2'	35	41	50	54	60
3-3’	43	43	44	48	60
4-4’	32	40	42	40	44

Points 1, 1’ and 2, 2’: Conductive Ink
Points 3, 3’ and 4, 4’: Conductive Paste

Table 6-9 Resistance Values of Samples made from Nylon-doped with silver Yarn

Unit: ohm

Path	0 cycle	1 cycle	5 cycles	10 cycles	20 cycles
1-1’	115	121	150	169	329
2-2’	113	112	122	141	178
3-3’	102	120	151	248	N/A
4-4’	110	122	178	507	520

Points 1, 1’ and 2, 2’: Conductive Ink
Points 3, 3’ and 4, 4’: Conductive Paste

6.4.5 Recommendation on Laundering the Sensate Liner

Thus, this extensive set of launderability trials has demonstrated the successful functioning of the interconnection technology and the choice of T-Connectors. It has also highlighted the need for conductive fibers that can withstand laundering and maintain their conductivity, a critical requirement for the successful commercialization of the technology for various applications.

6.5 The Concept of a Wearable Motherboard

As the research progressed and both the woven and knitted versions of the Sensate Liner were successfully designed, developed, and tested, a new concept emerged. The name “Wearable Motherboard” has been coined to better describe and encapsulate the overall concept and realization of the Sensate Liner, including the woven and knitted versions. Just as chips and other devices can be plugged into a computer motherboard, sensors and other information processing devices can be plugged into the woven and knitted Sensate Liners. Therefore, the name “Wearable Motherboard” is apt for the flexible, wearable, and comfortable woven and knitted Sensate Liners developed during the course of the research. We will now discuss the details of the architecture of the wearable motherboard.

6.5.1 The Wearable Motherboard Architecture

Figure 6-18 shows the architecture of the wearable motherboard along with the corresponding schematic in garment form with all the material components. The comfort or base fabric provides the necessary physical infrastructure. As discussed earlier, the base fabric is made from typical textile fibers where the choice of fibers is dictated by the intended application. The interconnection points are shown in the figure and together with the integrated conductive fibers, they form a flexible and wearable information infrastructure. The POF – integrated for projectile penetration – is also shown in the figure. Since the architecture is modular, POF will not be incorporated into the structure for non-combat applications of the Wearable Motherboard. The sensors can be positioned in desired locations on the body and will plug into the T-Connectors. As shown in the figure, the signals from the sensors flow through the flexible data bus integrated into the structure to the multifunction processor/controller. This device, in turn, processes the signals and transmits them wirelessly to desired locations (e.g., battlefield triage station, doctor's office, hospital, etc.). The bus also serves to transmit information to the sensors (and hence, the wearer) from external sources, thus making the fabric-based Wearable Motherboard a valuable information infrastructure.

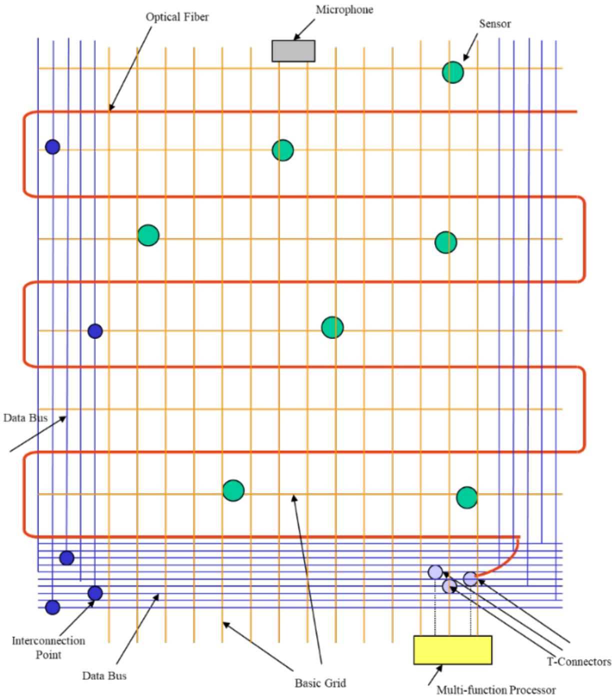


Figure 6-18 The Wearable Motherboard Architecture along with the Schematic in Garment Form
(a) Architecture

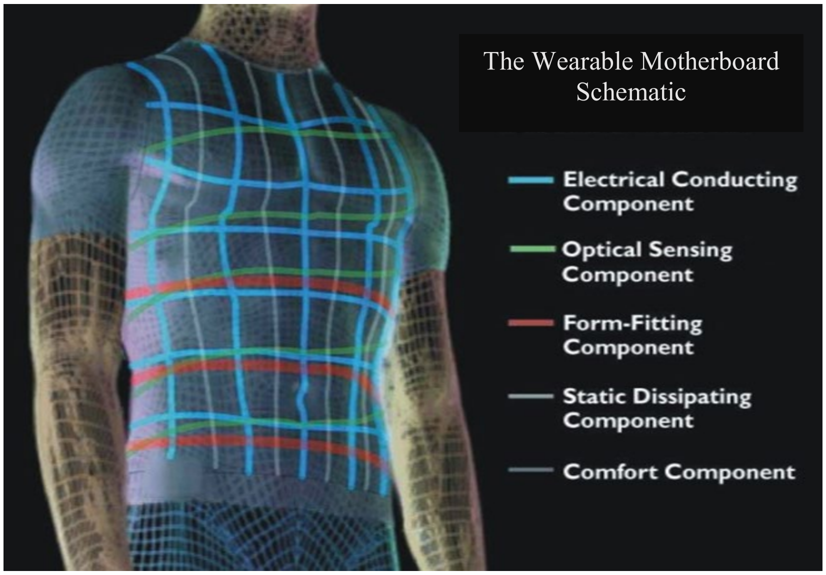


Figure 6-18 The Wearable Motherboard Architecture along with the Schematic in Garment Form
(b) Schematic

Just as the computer motherboard facilitates the “plug and play” concept (e.g., different graphics and sound chips can be plugged in to enhance the gaming experience for the user), different types of sensors can be easily plugged into the T-Connectors in the Wearable Motherboard. For instance, a sensor to detect oxygen levels or hazardous gases can be integrated into an instantiation of the Wearable Motherboard that can be used by firefighters. This information along with the vital signs from the other sensors plugged into the Wearable Motherboard can be transmitted to the fire station where personnel can continuously monitor the firefighter's condition and provide appropriate instructions including ordering the individual to evacuate the scene, if necessary.

Similarly, by plugging in a microphone, voice can be recorded or an MP3 player can be plugged in along with a pair of headphones so that the user could listen to music while jogging. Thus, the Wearable Motherboard opens up a new way to customize information processing devices to “fit the wearer by selecting and plugging in (or removing) chips/sensors from the fabric thus creating a personalized, wearable, mobile information infrastructure and spawns the paradigm of "Fabric is the Computer."

6.5.2 The Potential Applications

The creation of a *wearable information infrastructure* has opened up entirely new frontiers in personalized information processing, healthcare and telemedicine, and space exploration, to name a few. 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 space such as temperature, heart rate, etc.

Specifically, the Wearable Motherboard technology will have a significant impact on these key facets of human endeavor and will lead to the following:

Personalized Information Processing: A revolutionary new way to customize information processing devices to "fit" the wearer by selecting and plugging in (or removing) chips/sensors from the Wearable Motherboard.

Healthcare and Telemedicine: Enables monitoring and treatment of humans including those in post-operative recovery (e.g., heart surgery), geriatric patients (especially for those in remote areas where the doctor/patient ratio is very small compared to urban areas), mentally ill patients for a better understanding of diseases such as chronic depression, children susceptible to SIDS (sudden infant death syndrome), and individuals prone to allergic reactions (e.g., anaphylaxis reaction from bee stings).

Space Exploration and Specialized Monitoring Applications: Monitoring of astronauts in space in an unobtrusive manner and the knowledge to be gained from medical experiments in space that will lead to new discoveries and the advancement of the understanding of space. Likewise, the monitoring of firefighters, policemen and soldiers who encounter major threats in their lines of duty will significantly enhance their job safety and performance.

Spawning of a New Industry: Just as the home security industry is a big business that monitors and protects homes, the Wearable Motherboard technology has the potential to spawn a new industry for the reliable and effective monitoring of patients at home and thereby transform home healthcare delivery.

In short, the new paradigm spawned by the Wearable Motherboard provides an exciting opportunity that can not only lead to a rich body of new knowledge but in doing so, enhance the quality of human life. This research, which pioneered the integration of electronics with traditional textiles, has given birth to the field of "electronic or e-textiles" to represent this new class of textile structures with functional capabilities [54].

6.6 Research Outcome

This facet of research has led to the successful realization of the Sensate Liner for detecting projectile penetration and monitoring the vital signs of soldiers on the battlefield. The major building blocks of technology have been successfully integrated to create woven and knitted versions of the Sensate Liner. The research has also led to the novel concept of a “Wearable Motherboard.” The Wearable Motherboard is a fabric-based information infrastructure, which serves as a flexible and wearable framework into which sensors and devices can be plugged making it similar to a motherboard in an electronic device. This represents true convergence between electronics and textiles giving birth to the new field of electronic or “e-textiles.” The modular architecture of the Wearable Motherboard enables the user to control the degree of convergence based on the desired application.

CHAPTER 7

Versatility of the Wearable Motherboard Paradigm: Exemplary Applications

In this Chapter, we present a few typical real-world scenarios and discuss the need for personalized mobile information processing and the role of human as an "information node." We present the concept of clothing as a universal interface and its important role in serving as a "platform" for harnessing ambient intelligence. We then demonstrate the value of the Wearable Motherboard paradigm through its instantiation for a variety of applications using the design and development methodology developed in Chapter 2.

7.1 Personalized Mobile Information Processing: The Opportunity

The significant advancements in computing and communications technologies are fundamentally changing when, where and how individuals work and live. No longer confined to a "workplace" or chained to a static computing infrastructure, anyone can process information anytime and anywhere giving birth to the paradigm of pervasive information processing or "information processing on the go." The advancements in, and convergence of, microelectronics, materials, optics and bio technologies, coupled with miniaturization, have led to the development of small, cost-effective intelligent sensors for a wide variety of applications. The transparency of the user interface coupled with the invisibility of the "embedded" technology in the various devices and systems have contributed to the proliferation of these sensors in various applications. By effectively harnessing the benefits of these technological advancements, it is possible to create a system that can provide access to the right information at the right time in the right place, which can indeed make a difference between life and death [55].

7.1.1 The Three Scenarios

Let us consider an individual with a newly implanted pacemaker who is getting back to normal routine established prior to the surgery, albeit at a different pace. During the course of a typical day, the individual is likely to engage in activities such as working, walking, shopping, exercising, etc. in different geographically distributed locations such as an office, hospital, gymnasium, theatre, restaurant, etc. as shown in Figure 7-1. On one such day, while at work, the individual suddenly has a stroke and is rushed to the hospital. If information about the individual's condition were being transmitted to the hospital even as the individual is being rushed there, the doctors in the hospital can prepare in advance to provide speedy and safe treatment and, hopefully, ensure the individual's survival.

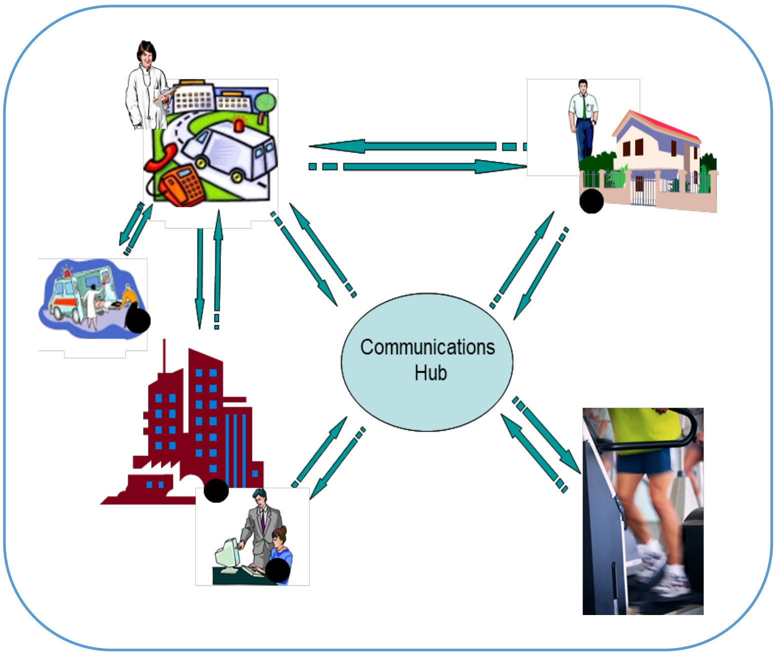


Figure 7-1. A Day in the Life of an Individual with a Pacemaker

Consider a soldier in an urban warfare scene who is in constant communication with the remote command and control center. Unfortunately, casualties are associated with protection of citizens and preservation of national security – be they soldiers engaged in combat with the enemy (as in this scenario) or first responders saving the lives of innocent victims subjected to terrorist attacks. As shown in Figure 7-2, both soldiers and first responders must – in a very short period of time – go into "high-risk" environments about which there is no *a priori* knowledge, viz., the type of potential threat, including possibly nuclear, chemical or biological, to name a few. Lack of proper and timely information, and hence knowledge, about the highly dynamic environment is hazardous to those individuals who need to operate in them.

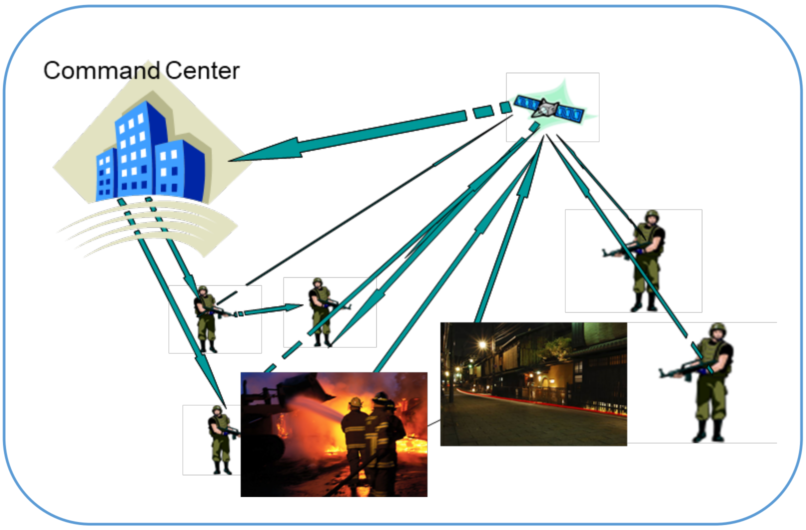


Figure 7-2. An Urban Warfare Environment: Soldiers and First Responders

Situational or contextual awareness is critical both for the soldier/first responder engaged in the operation and for the commanders coordinating and leading the engagement. The commanders must sense and extract the information from the dynamic environment in real-time, adapt and respond appropriately to the potential threat, viz., send in reinforcement, ask the soldier/first responder to change course or return to the base, thereby minimizing risk to them. For instance, if the first responder suddenly encounters hazardous gases, it is important for the responder and his commanders to know the hazard type so that he can protect himself (using appropriate masks or taking antidotes) and evacuate safely. In the case of the soldier, if he were shot, information about the soldier's location, physical condition (e.g., heart rate and electrocardiogram) and location of the wound on the body will be critical in locating, reaching and attending to the soldier within the so-called "Golden Hour" to prevent a fatality.

Finally, consider a day in the life of a college student. As shown in Figure 7-3, during the course of the day, the student is in class, in the cafeteria, studying, rock-climbing outdoors with friends, listening to music, and so on. When playing on-line, if the pace and intensity of the game are automatically adjusted by the system depending on the student's physical conditions, say the heart rate, then the adaptive game can maximize the enjoyment for the gamer while minimizing potential risks to his/her health. Likewise, monitoring the mental health of students is becoming increasingly critical: "In spring 2017, nearly 40% of college students said they had felt so depressed in the prior year that it was difficult for them to function, and 61% of students said they had "felt overwhelming anxiety" in the same time period [56]."

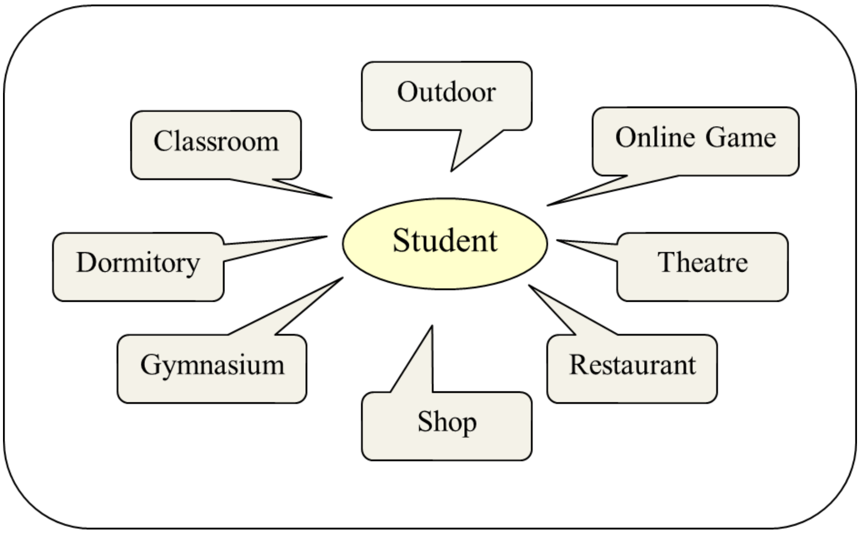


Figure 7-3 A Day in the Life of a College Student

7.1.2 Human as an Information Node: Need for Personalized Mobile Information Processing

A careful analysis of these three seemingly different scenarios reveals a few similarities depicted in Figure 7-4. First, the human, in each instance, acts as the information node or a sensor acquiring contextual or situational information from the scene. If the individual in the first scenario is suddenly experiencing chest pains and the individual's information is communicated to the hospital immediately, it can trigger an emergency response process there awaiting the arrival of the ailing patient. In the firefighting scenario, the firefighters themselves become "information nodes" in a human ad hoc network and provide valuable information from the fire scene to the situation command center established away from the fire scene. The individual, in essence, is a "sensor" in this network that is collecting and processing information in real-time.

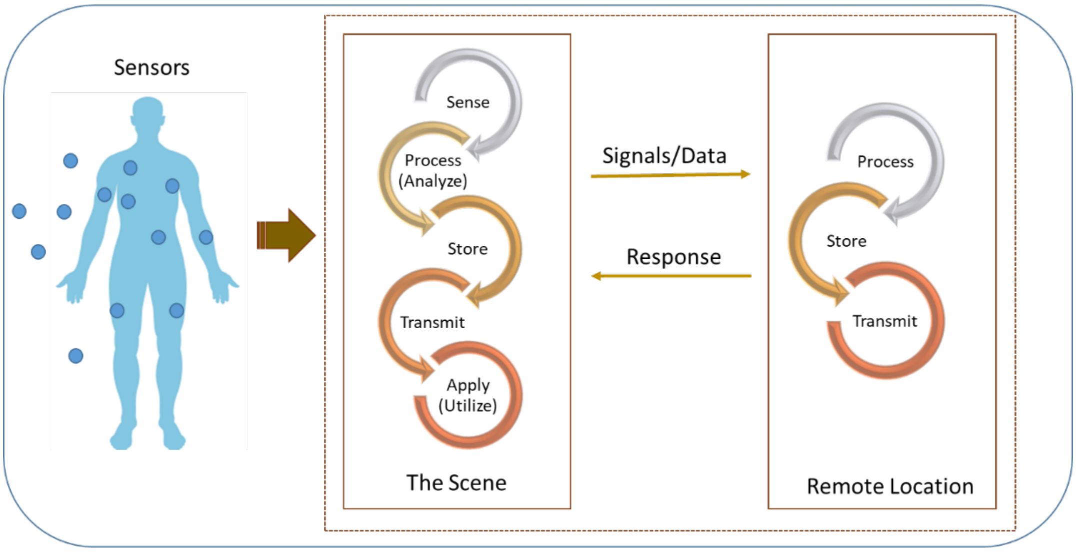


Figure 7-4. Personalized Mobile Information Processing: The Unit Operations

Second, the information from the individual as the information node is processed both locally on board the individual and remotely at the back-end, which typically will have greater processing power (hardware/software and human expertise). Third, the results (from both places) are used at the scene to take the recommended course of action so that the individual's quality of life (through better gaming for the college student) or chances of survival (through life-saving intervention for the heart patient or withdrawal from the scene for the soldier) are enhanced.

In each scenario, the individual is typically mobile; so, the information processing must occur on the go. The information is specific to the individual and the scene, which means it must be personalized while harnessing the contextual information. Therefore, what is needed is personalized mobile information processing, or PMIP for short, which can transform the sensory data to information and then to knowledge that can be gainfully employed by the individual in suitably adapting the response to the situation. Moreover, *any* technology or system that can minimize the loss of human life and/or enhance the quality of life is priceless.

7.1.3 Personalized Mobile Information Processing: The Technology Building Blocks

Harnessing contextual or ambient intelligence calls for the effective management of the information in and from the ambient environment. Specifically, this involves addressing the unit operations shown in Figure 7-4. Sensors are required for acquiring signals (information) from the individual at the scene and the environment (as appropriate) to provide contextual or situational awareness. The types of sensors deployed depend on the application. For instance, in the case of the civilian with the pacemaker, the sensor suite would include those for monitoring vital signs, listening to music during workouts, a microphone for recording food intake and exercise regimens, etc. For the soldier, additional sensors could include those for detecting penetration (due to shrapnel), sensing hazardous gases, identifying location and posture, among others. In the case of the gamer, the sensor suite for the civilian is augmented with motion and gesture sensors. Thus, the sensor suite would be application-specific.

The signal processing system must then process the signals – biometric, video, location, motion, position, environmental, etc. – and compute the appropriate parameters (in the case of vital signs, they could include heart rate, body temperature, and electrocardiogram). Part of the processing, say signal noise reduction and analog to digital conversion, can occur at the scene and the heavy-duty processing can occur at the back-end in the remote location that will have the necessary hardware and software capabilities.

The communications system must then transmit the processed data to the remote location (e.g., hospital, battlefield or fire command and control center) for analysis and, optionally long-term storage. There, a knowledge-based decision support system can aid the domain experts in analyzing the data and recommending optimal responses.

Together, these building blocks constitute the system for harnessing situational intelligence and enabling personalized mobile information processing.

7.1.4 Meeting the Need: The Sensor Network Paradigm

A structured analysis of the sensing technology building block leads to the following requirements [57]:

1. Different types of sensors are needed for the various parameters to be monitored simultaneously; for instance, the sensors to monitor the various vital signs (e.g., heart rate, body temperature, pulse oximetry, blood glucose level) are of different types. Likewise, for monitoring hazardous gases, another class of sensors (e.g., Carbon Monoxide detection) will be required. Accelerometers will be required to continuously monitor the posture of the gamer or an elderly person to detect falls;
2. Different numbers of sensors may be needed to obtain the signals to compute a single parameter (e.g., at least three sensors are required to compute the electrocardiogram or EKG);
3. The sensors need to be positioned in different locations on the body to acquire the necessary signals (e.g., sensors for EKG go in three different locations on the body whereas the pulse-ox sensors and accelerometers go in other locations on the body);

4. Different subsets of sensors and devices may be used at different times necessitating their easy attachment and removal, or plug and play. For instance, the astronaut may want to record how the body feels and reacts while taking a spacewalk and would need a microphone and recording device only at that time;
5. The signals from the various sensors, and in different locations have to be sensed, collected, processed, stored, and transmitted to the remote location;
6. Signals from multiple sensors of the same type (e.g., EKG) have to be simultaneously aggregated to compute a single parameter (e.g., EKG waveform);
7. Signals from different types of sensors (e.g., body temperature, EKG, accelerometers) have to be processed in parallel to evaluate the various parameters in real-time;
8. The large numbers of sensors to be deployed would require that the sensors be of low cost and hence will have minimal built-in (on-board) processing capabilities;
9. The sensors should be power-aware (i.e., have low power requirements); and
10. Power must be supplied (distributed) to the various sensors and processors.

Thus, there is a need for a sensor network that effectively meets these design/performance requirements. The sensor network must be able to *host* or hold the various sensors in place and provide data buses or pathways to carry the signals (and power) from and to the sensors and the information processing components in the network. The sensor network must be lightweight, unobtrusive and should interface naturally with the user. It should always be “on” the individual since it must harness the user's contextual awareness to facilitate personalized mobile information processing. It should therefore be a wearable sensor network.

7.1.5 Salient Features of Textiles: Fulfilling the Human Factors Needs

Humans are used to wearing clothes from the day they are born; in general, no special 'training' is required to wear them, i.e., to use the interface. In fact, it is probably the most universal of interfaces and is one that humans need, use, have familiarity with, and which can be easily customized [58]. This "universal interface" of clothing is in contrast to typical computer interfaces/systems (e.g., Unix®, Windows®, Linux®, iOS®, Android®) each of which has some unique characteristics and requires time and effort to learn to use. Moreover, humans enjoy clothing and this universal interface of clothing can be 'tailored' to fit the individual's preferences, needs and tastes including body dimensions, budgets, occasions and moods. Textiles are designed to accommodate the constraints imposed by the ambient environment in which the user interacts, i.e., different climates or operating requirements, and still keep the user comfortable.

Textiles are pervasive: They span the continuum of life from infants to senior citizens and from astronaut's space suits (denoting functionality) to elegant evening dresses (denoting fashion). In addition to these two dimensions of functionality (or protection) and fashion, if 'intelligence' can be embedded or integrated into textiles as a third dimension, it would lead to the realization of clothing as a personalized and flexible wearable information infrastructure [59].

7.1.6 Meeting the Performance Requirements: Role of Textiles and Clothing

Textiles or clothing will meet the various technical performance requirements of a wearable sensor network for personalized mobile information processing because they [60, 61]:

1. Provide data buses or communication pathways for the sensors and processors in the form of textile yarns, which are an integral part of the fabric. The topology, or structure of placement of these data buses, can be engineered to suit the desired sensor surface distribution profile;
2. Are flexible, strong, lightweight, and shape-conformable. Textiles, unlike other engineering structures such as buildings, are unique in combining strength and flexibility in the same structure and so they conform to the desired shape when bent but retain their strength;
3. Can be made in different form factors including desired dimensions of length and width, and hence "variable" surface areas that may be needed for "hosting" varying numbers of sensors and processors in the sensor network;
4. 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;
5. Are easy to manufacture in a relatively cost-effective (inexpensive) manner compared to traditional printed circuit boards;
6. Obviate issues associated with entanglement and snags that can arise when deploying the sensor network since the data buses or communication pathways are an integral part of the fabric;
7. Can easily accommodate "redundancies" in the system by providing multiple communication pathways in the network; and

8. Enable easy power distribution from one or more sources through the textile yarns integrated into the fabric, thus minimizing the need for on-board power for the sensors.

Thus, from a technical performance perspective, a textile fabric is an ideal platform for the incorporation of sensors and processors to create a wearable sensor network for personalized mobile information processing. We now illustrate the role of the Wearable Motherboard in serving as this ideal platform through a few of the potential applications shown in Table 7-1. The design and development framework shown in Figure 2-2 (discussed in Section 2.4) has been used for this purpose. This also illustrates the versatility of the methodology developed on this research to systematize the process of designing textile structures and systems for a multitude of applications.

Table 7-1 Potential applications of the Wearable Motherboard [58]

Segment	**Application Type**	**Target Customer Base**
Civilian	Medical Monitoring (Vital Signs, Falls, Pressure, Strain)	Patients: Illnesses, Surgical Recovery, Psychiatric Care
		Senior Citizens: Geriatric Care, Nursing Homes
		Infants: SIDS Prevention
		Teaching hospitals and medical research institutions for new pharmaceuticals and treatments
	Rehabilitation (Exercise, low back pain therapy, motor exercise)	Patients: Elderly, Injured, Post-stroke, Sports
	Sports/Fitness/Performance Monitoring (Vital signs, sweat analysis)	Athletes, Individuals
		Scuba Diving, Mountaineering, Hiking
Military	Combat Casualty Care (Shrapnel penetration, vital signs, location, voice)	Soldiers and Support Personnel in Battlefield
Specialized	Mission Critical/Hazardous Applications (Working conditions, fatigue, sleepiness, voice)	Mining, Mass Transportation
Public Safety	Disaster Response (Vital signs, Exposure to dangerous materials, location, voice)	First Responders / Firefighters
	Law Enforcement (Vital signs, bullet wounds, exposure to dangerous materials, location, voice)	Police
Entertainment	Gaming (Vital signs, Posture)	Gamers
	On-Stage Performances (Action-based response)	Entertainers
Fashion	Illuminated Dresses (Fashion, fun)	Entertainers, Consumers
Space	Space Experiments (Vital signs, video, voice)	Astronauts
Universal	Wearable Mobile Information Infrastructure	All Information Processing Applications

Figure 7-5 shows the flowchart of operations involved in instantiating the Wearable Motherboard for a specific application.

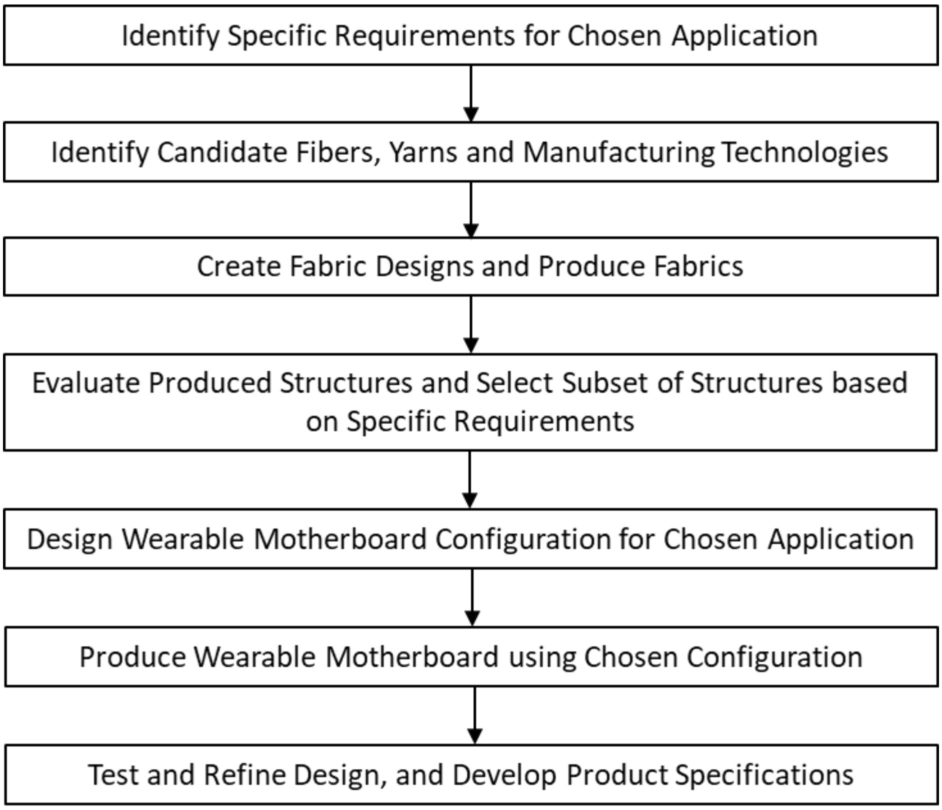


Figure 7-5. Process Flowchart for Instantiating the Wearable Motherboard for Specific Applications

7.2 Instantiation of the Wearable Motherboard: Physiological Monitoring

To demonstrate the versatility of the Wearable Motherboard paradigm, a physiological monitoring version has been created for adults to monitor the heart rate, respiration rate and electrocardiogram (EKG) using three leads. Since the form factor is a garment, it is named the Smart Shirt.

7.2.1 Sensor Architecture in the Smart Shirt

Based on a review of literature in the area of EKG monitoring [62] and discussions with physicians, several layouts have been created for positioning the EKG sensors on the body (shirt). Smart Shirts with different positions of the sensors have been created and tested in the laboratory with the Dynamap EKG monitor. The quality of the signals (artifacts) and the end user's comfort were evaluated along with the propensity of the sensors to come unplugged from the Smart Shirt due to typical movements. These studies led to a three-lead EKG configuration shown in Figure 7-6.

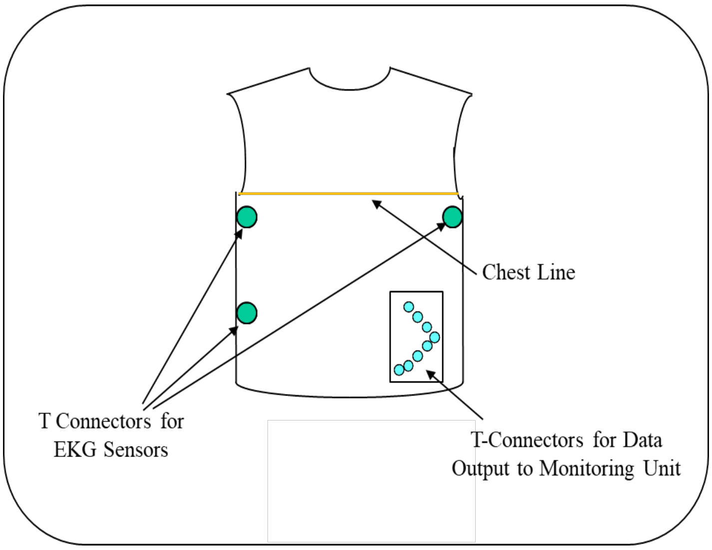


Figure 7-6. Sensor Architecture Template for Smart Shirt with Three-Lead EKG Monitoring

7.2.2 Specifications of the Medical Version of the Smart Shirt

The specifications of the medical version of the Smart Shirt are shown in Table 7-2. The capabilities to monitor the body temperature using a temperature sensor and to record voice using a microphone (connected to a laptop) have also been integrated to demonstrate the "plug and play" feature of the Wearable Motherboard.

The fabric has been knitted on a Shima-Seiki knitting machine and the interconnections made using the technology discussed in Chapter 4.

Table 7-2. Specifications of the Medical Version of the Smart Shirt

Base Fiber Type	Cotton with Core-Spun Lycra (50:50)
Base Yarn Count	60/2s Ne
Conductive Fiber Type	PVC Insulated Stainless Steel
Conductive Yarn Count	1034 Denier
WPI/CPI	20/28
Manufacturing Technology	Knitting
Sensors	Silver Chloride Gel-based Sensors
Parameters Monitored	Heart Rate, Respiration Rate, Electrocardiogram (EKG) using three leads, Body Temperature using a thermistor sensor, Voice monitoring using a microphone
Monitoring Equipment Interface	Dynamap EKG Monitoring System and Nihon-Kohden Wireless Monitoring System (WEP-8400A Model)

7.2.3 Field Testing and Demonstrations of the Medical Version of the Smart Shirt

The medical version of the Smart Shirt is shown in Figure 7-7. It has been tested at an area hospital using the Nihon-Kohden EKG monitor [63]. The subject wore the garment and plugged the EKG sensors on the body into the appropriate T-connectors in the garment. The transceiver was then connected to the T-Connectors on the Smart Shirt. This created the path for the signals from the body to flow through the sensors and the data buses in the garment to the transceiver, which wirelessly transmitted it to the monitor.

Microphone is plugged in here for recording voice

Multifunction processor is plugged into the T-Connectors here. Transmits data wirelessly to EKG monitoring equipment.

Figure 7-7. Medical Version of the Smart Shirt

The testing has been carried out under three conditions. Initially, the subject was stationary and the data (heart rate, respiration rate and EKG waveform) were recorded in the machine. Then the subject walked at a measured pace in the hospital and the transceiver was able to transmit the data to the monitor and the signals were clean (Figure 7-8). The subject walked very fast in the hospital and the monitor picked up the data (Figure 7-9). Finally, the user ran in the hospital and the recorded vital signs and waveform are shown in Figure 7-10. For each test condition, vital signs were also recorded directly from the wearer, i.e., without the Smart Shirt denoted by “Control: Electrodes on Body” in the figures.

Figure 7-8. User Walking at Normal Speed with the Nihon-Kohden Wireless Monitoring System

Top Trace: Vital Signs through the Smart Shirt
Bottom Trace: Vital Signs Directly from the User (No Smart Shirt)

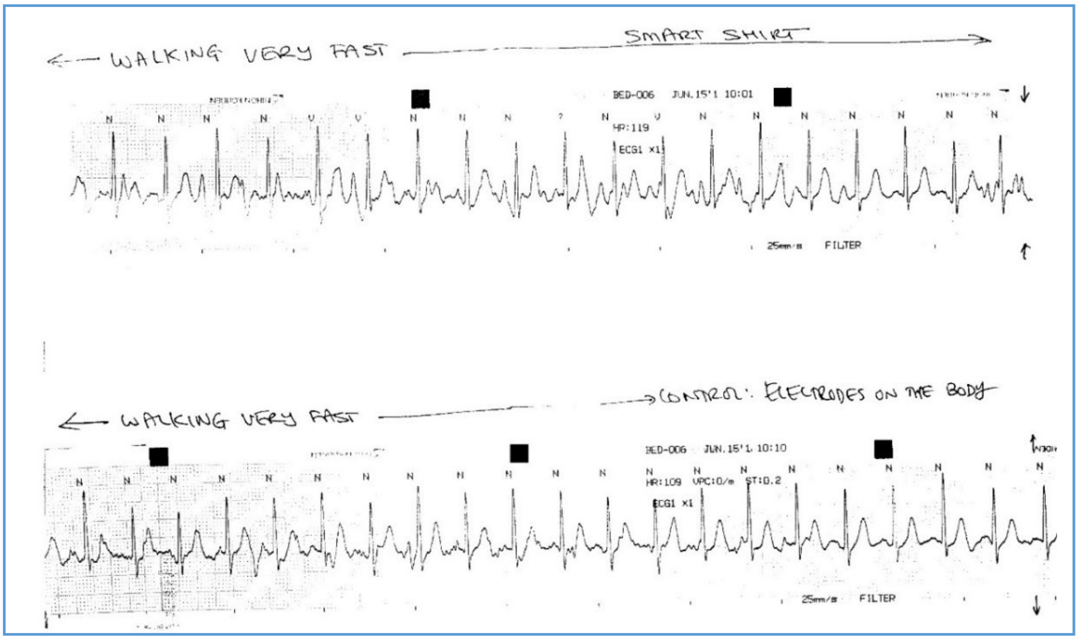


Figure 7-9. User Walking Very Fast with the Nihon-Kohden Wireless Monitoring System

Top Trace: Vital Signs through the Smart Shirt
Bottom Trace: Vital Signs Directly from the User (No Smart Shirt)

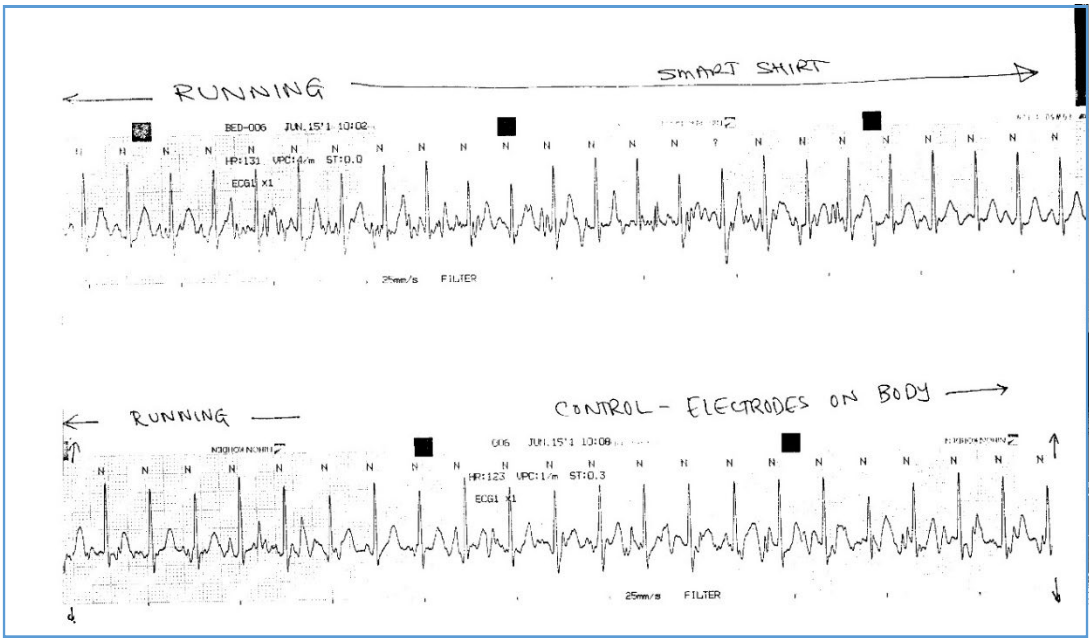


Figure 7-10. User Running with the Nihon-Kohden Wireless Monitoring System

Top Trace: Vital Signs through the Smart Shirt
Bottom Trace: Vital Signs Directly from the User (No Smart Shirt)

This series of tests has demonstrated the seamless integration between the Smart Shirt and a commercially available wireless EKG monitoring system; it also illustrates the ability of the Smart Shirt to function effectively even when the user is mobile. The user was comfortable during the tests and felt that the Smart Shirt was like a typical undershirt.

A microphone was connected to the Smart Shirt and the user’s voice was recorded to further demonstrate the functionality of the Smart Shirt as an information processing platform. The sensor architecture for this instantiation of the Wearable Motherboard is shown in Figure 7-11.

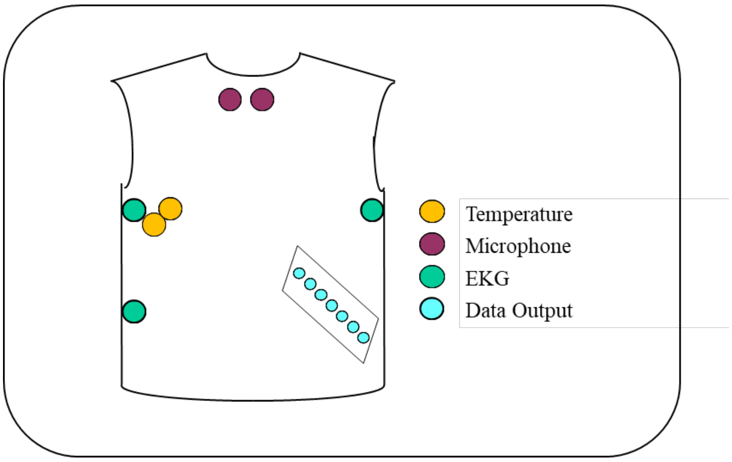


Figure 7-11. Sensor Architecture Template for Smart Shirt with Voice Recording, Temperature Sensing, Heart Rate, Respiration Rate and EKG Monitoring Features.

Figure 7-12 shows another instantiation of the sensor architecture that has been overlaid on a garment created for a race car driver; this garment was then successfully tested with the car driving at speeds over 180 miles/hour. Figure 7-13 shows the EKG trace whenever the driver approached the range of the 802.11b wireless network associated with the monitoring equipment located in the pit on the side of the race track.

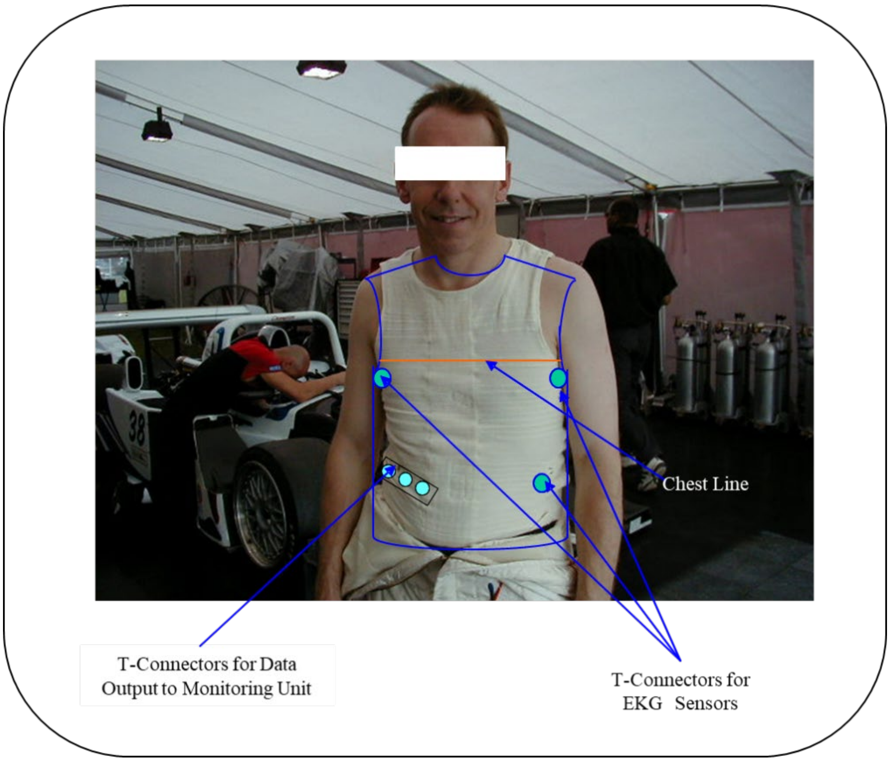


Figure 7-12. Sensor architecture overlaid on Smart Shirt for race car driver

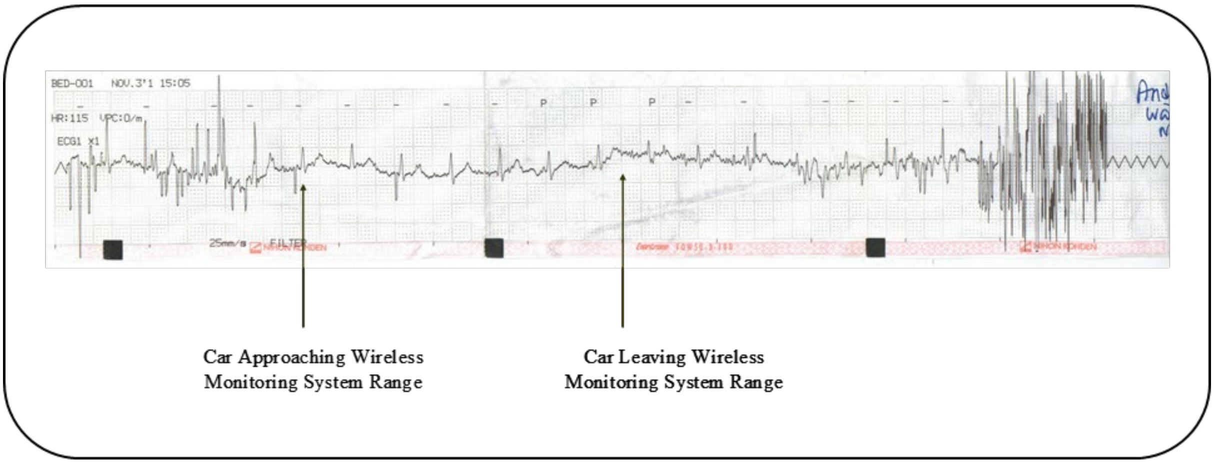


Figure 7-13. EKG Trace from race car driver whenever car reaches the monitoring range

Thus, the successful realization of the physiological monitoring version of the Smart Shirt illustrates the versatility of both the design and development methodology presented in Chapter 2 and the Wearable Motherboard paradigm.

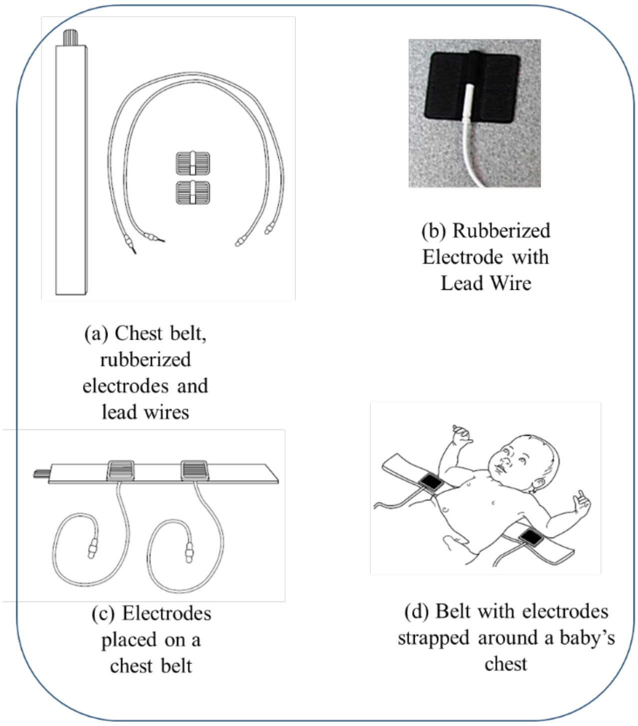
7.3 Instantiation of the Wearable Motherboard: The SIDS Application

Sudden Infant Death Syndrome (SIDS) is defined as the unexpected death of an infant under one year of age that is unexplained by history, postmortem exam, and death scene investigation [64, 65]. SIDS is the leading cause of post-neonatal mortality in the United States, accounting for almost 40% of deaths in infants from one month to one year of age. Approximately seven of every 10,000 live born infants in the United States succumb to SIDS. Specific groups of infants have been identified to be at “high risk” for dying suddenly and unexpectedly and include premature infants, siblings of SIDS victims, and infants who have experienced “Apparent Life-Threatening Episodes” (turned blue and/or stopped breathing). Georgia and the Southeast are lagging behind the national trend in the decrease in deaths from SIDS because parents here do not follow the proper guidelines when putting children to sleep [66].

7.3.1 The Key Problems with Infant Monitoring Systems

A major problem with home monitoring of infants is noncompliance. There are two main reasons why families are reluctant to use home monitors. The first is due to the electrodes that are used to record the heart rate and respiratory effort. Rubberized electrode patches are first placed on the child’s chest; these are held in place by applying a Velcro belt over the patches.

Figure 7-14 shows the electrodes, the chest belt and lead wires for one of the common home monitoring systems for babies. If not applied properly, the belt and/or electrodes irritate the infant’s skin (sometimes to the point of blistering and even bleeding); therefore, the parents stop using the equipment.



(a) Chest belt, rubberized electrodes and lead wires

(b) Rubberized Electrode with Lead Wire

(c) Electrodes placed on a chest belt

(d) Belt with electrodes strapped around a baby's chest

Figure 7-14. Rubberized electrodes with lead wires and chest belt for SIDS Monitoring [67]

The second major cause of non-compliance relates primarily to "older" infants who can roll over. In this instance, the parents are afraid that the wires will "wrap around the child's neck." Figure 7-15 shows the child with the belt and electrodes connected to the monitor with the lead wires. Again, they stop monitoring the child.

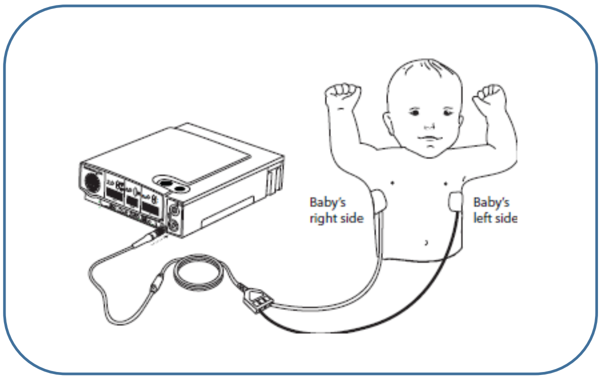


Figure 7-15. Lead wires connected to the Monitor [68]

7.3.2 Addressing the Challenge: The Potential of the Wearable Motherboard

The Wearable Motherboard paradigm has the potential to provide a *solution* to the twin problems associated with noncompliance for two principal reasons. First, the sensors can be "plugged" into the Wearable Motherboard that is like any undershirt, which can be customized to fit the child; thereby, the discomfort from the existing Velcro belt is minimized while ensuring the correct and easy placement of the sensors in the right positions. Second, the wires that lead to the monitoring device can be plugged into the hip/waist level of the Wearable Motherboard and thereby minimize any risk of the infant getting wrapped around by the wires.

Therefore, research has been carried out to address these twin challenges. The primary objective has been to create and test a garment for monitoring infants prone to SIDS. This has been accomplished by identifying the specific requirements for monitoring, using the design and development methodology to create an infant version of the Wearable Motherboard, and testing its functionality, wearability and usability in the field. This research has been carried out in collaboration with the Emory Apnea Center at Children's Healthcare of Atlanta.

At the Apnea Center, infants are followed on home cardiorespiratory monitors that record a child's heart rate (including the actual EKG waveform) and chest wall movements. If certain preset parameters for apnea and/or bradycardia are violated, two functions occur. First, the monitor alarms to warn the caregiver of a problem. Second, the monitor records the EKG, trend event of the heart rate, and the respiratory waveforms. This data is downloaded at the Apnea Center to verify the events. Thus, the system saves lives by alerting the caretaker that an infant has stopped breathing or dropped his/her heart rate below a "safe" level. Moreover, in certain instances, the

Apnea Center has been able to diagnose unsuspected heart blocks, arrhythmias, and even seizures that were unsuspected by the primary care physician [69].

7.3.3 IRB Approvals: Informed Consent Form and Logbook for Evaluation

The first step has been to develop the testing protocol and seek Institutional Review Board (IRB) approval for the study from Emory University and Georgia Tech, respectively. Since the technology is new, the study has focused on “healthy” infants rather than on infants at-risk for SIDS. An informed consent form has been created as part of the IRB application. A detailed logbook for use by the caregiver during testing has been prepared. It addresses the following components critical for the study:

1. The Purpose
2. Washing Instructions
3. Performance Recording Chart (False Alarms)
4. Smart Shirt Usage
5. Smart Shirt Wash Chart
6. Smart Shirt Ease of Use Chart
7. General Set of Questions

The logbook also provides information on the points of contact during the course of the evaluation so that the caregiver could immediately contact the researchers with any questions or concerns during the testing.

7.3.4 Development of the SIDS Version of the Smart Shirt

The study was begun after obtaining approvals of the IRB applications at both institutions. The two healthy infants chosen for the study were under the care of the Apnea Center, but were monitored at home by their caregivers using the SmartMonitor from Respironics [70]. By carrying out the studies in sequence (on the two babies), the results from the first evaluation could be used to enhance the design of the Smart Shirt and thereby achieve the “final” garment design despite the small sample. The first step was to explain the details of the planned research to the caregiver using the Informed Consent Form. Once consent was obtained, the baby’s measurements were taken to create a version of the Wearable Motherboard for the baby. The ease with which the garment could be put on and taken off was highlighted as one of the key requirements by the caregiver.

The design and development framework discussed in Chapter 2 has been instantiated to create the architecture of the infant version shown in Figure 7-16. The details of the architecture including the various components are shown in Figure 7-17.

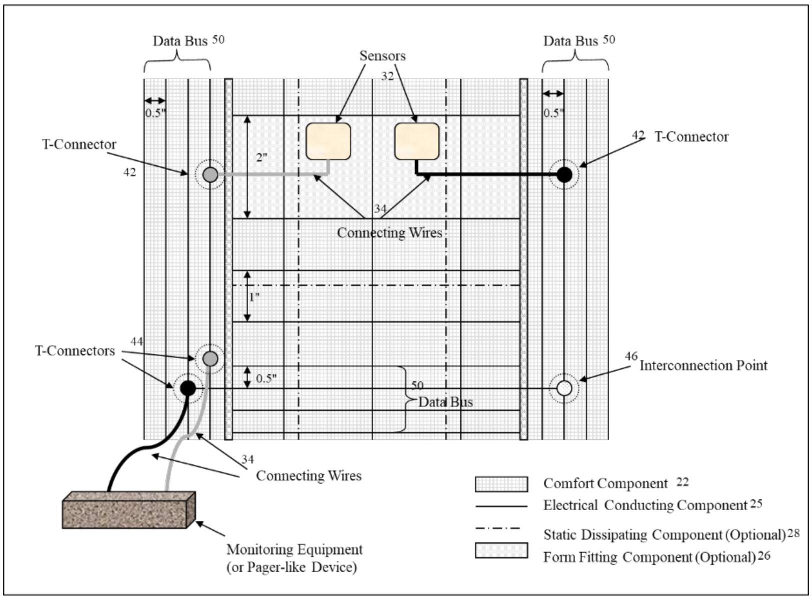


Figure 7-16. Architecture of the Infant Version of the Smart Shirt for SIDS Monitoring.

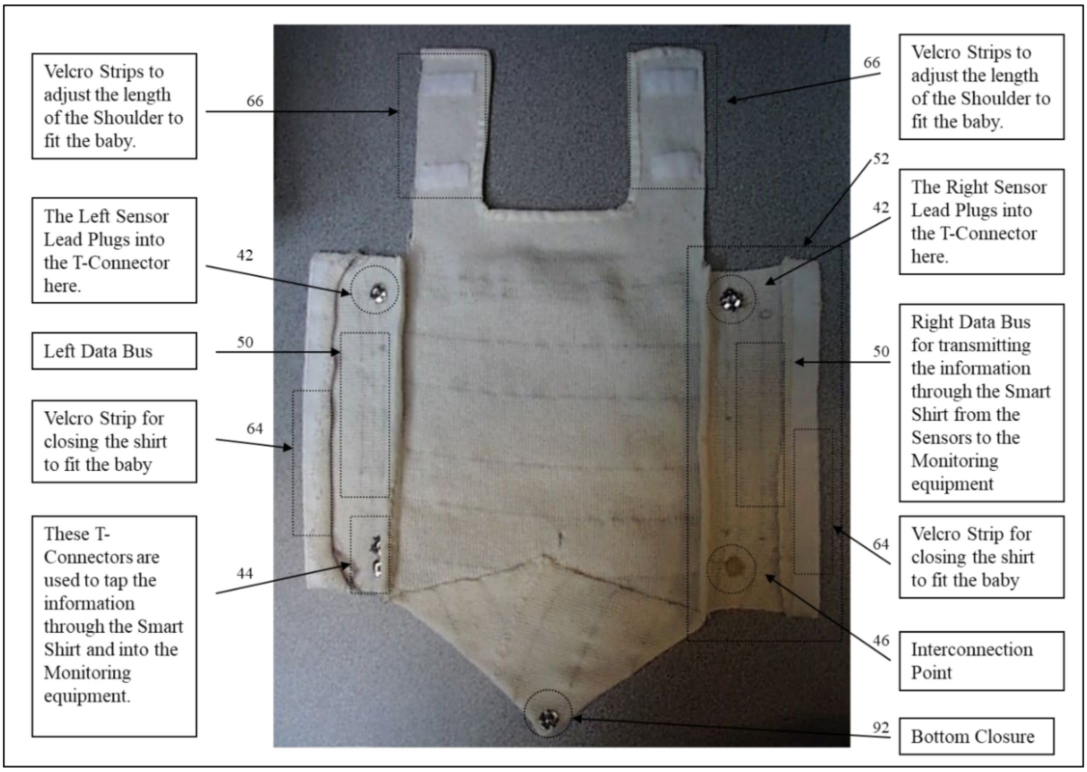


Figure 7-17. Details of the Architecture showing the Various Components in the SIDS Garment.

After several iterations, the two designs shown in Figures 7-18 have been created. Given the nature of the application, which required a snug fit, knitting was chosen as the manufacturing method (instead of weaving). Then the yarn type (fiber, count, twist, etc.) and fabric architecture (wale/course densities, stitch type, etc.) were finalized for the comfort component and the data bus in the garment. Using the dimensions of the infant, garments have been produced in the lab at Georgia Tech. Table 7-3 shows the specifications.

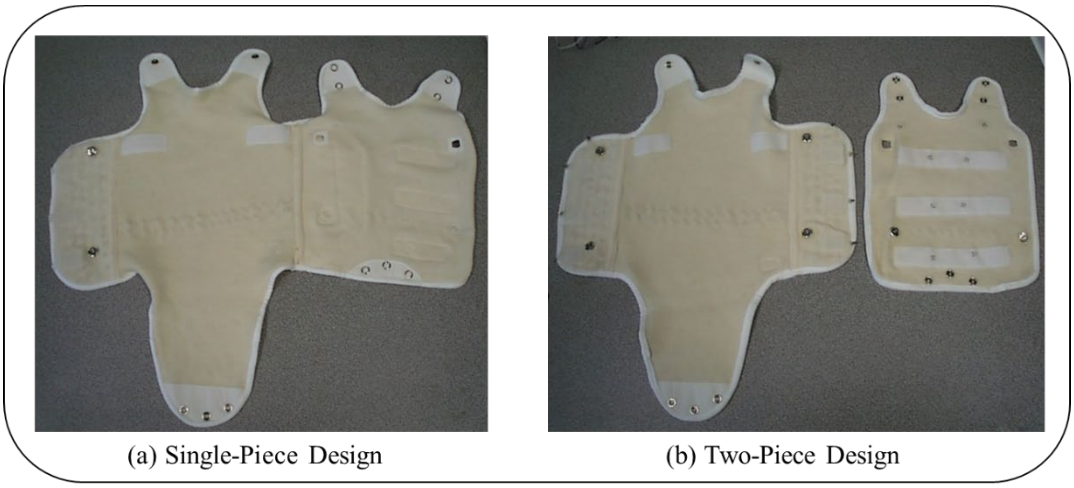

(a) Single-Piece Design
(b) Two-Piece Design

Figure 7-18. Two Designs of the Infant Smart Shirt for SIDS Monitoring

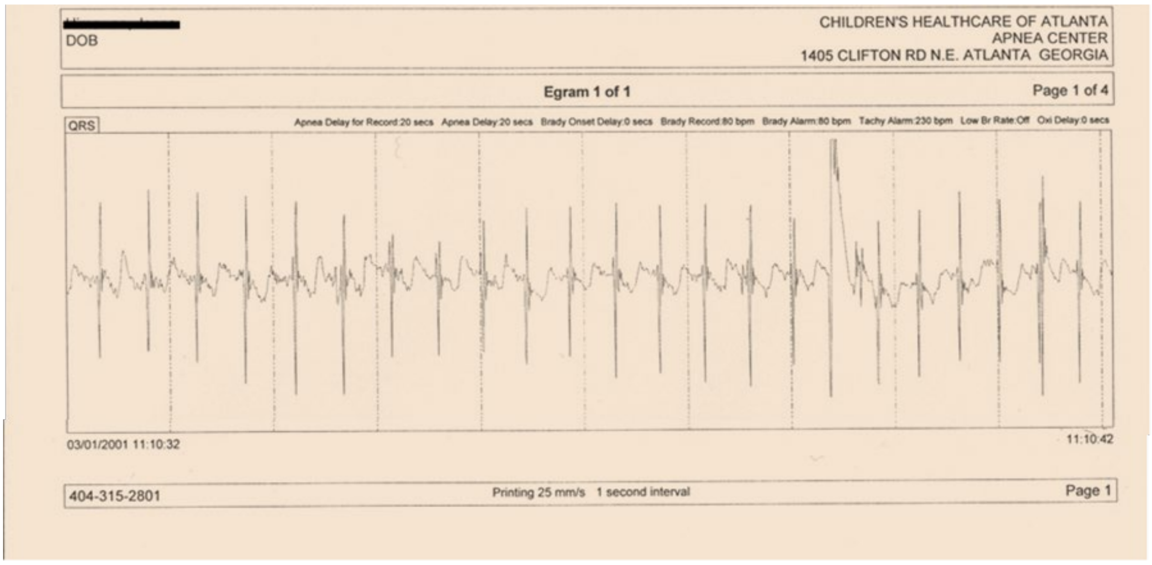
Table 7-3. Specifications of the Infant Smart Shirt for SIDS Monitoring

Base Fiber Type	100% Cotton
Base Yarn Count	30s Ne, 3 ply
Conductive Fiber Type	Silver Doped Nylon and Stainless Steel
Conductive Yarn Count	1034 Denier
WPI/CPI	44/68
Manufacturing Technology	Knitting
Sensors	Silver Chloride Gel-based Sensors
Parameters Monitored	Heart Rate, Electrocardiogram (EKG) using two leads
Monitoring Equipment Interface	Respironics SmartMonitor™

7.3.5 Testing and Evaluation

The infant garments and the Logbook were delivered to the caregiver after obtaining the informed consent. A “fit and use” session was held with the baby and caregiver to explain and demonstrate how the sensors were to be plugged into the garment and how the total system was to be used. During the course of the evaluation, the researchers periodically interacted with the caregivers. At the end of the study, debriefing sessions were held with the caregivers to obtain their assessments of the technology. No compensation was paid to the study participants.

In the study, the garment was used on the baby during three scenarios, viz., when the baby was lying down, being carried around, and playing with the parents, respectively. No false alarms were reported during use and only when the Smart Shirt was taken off did the Respironics monitor record an "event." The snapshot of the EKG traces prior to the "event" looked normal as shown in Figure 7-19.



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DOB

CHILDREN'S HEALTHCARE OF ATLANTA
APNEA CENTER
1405 CLIFTON RD N.E. ATLANTA GEORGIA

Egram 1 of 1 Page 1 of 4

QRS Apnea Delay for Record:20 secs Apnea Delay:20 secs Brady Onset Delay:0 secs Brady Record:80 bpm Brady Alarm:80 bpm Tachy Alarm:230 bpm Low Br Rate:Off Oxi Delay:0 secs

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404-315-2801 Printing 25 mm/s 1 second interval Page 1

Figure 7-19. EKG Trace from the Infant Version of the Smart Shirt (Information identifying the subject has been marked out in the figure)

During the briefing at the end of the study, the caregivers were very pleased with the usability of the garment and preferred the "single-piece" version as being convenient to handle, i.e., to put on and take off. Also, the risk of losing one of the "pieces" of the two-piece garment was suggested as a potential problem. In one caregiver's words, "The garment is ready to go to the real world."

The absence of false alarms during the test also confirms the functionality of the Smart Shirt; moreover, this facet of having no false alarms bodes well for the adoption and use of the technology, thereby enhancing compliance. This successful test has demonstrated both the versatility of the design and development methodology and the value of the Wearable Motherboard paradigm to enhance the quality of life for individuals whose children might be prone to SIDS [71].

7.4 Instantiation of the Wearable Motherboard: The In-Fabric Network for PMIP

To demonstrate yet another strength of the Wearable Motherboard paradigm, viz., its role as a platform for personalized mobile information processing (PMIP), research has been carried out to design and create an "in-fabric" network in which information flows through the textile fabric infrastructure and the flow is regulated/channeled by a microprocessor integrated into the fabric. This investigation of "fabric is the computer" paradigm will facilitate the development of an adaptive and responsive wearable computational fabric system. Such a fabric can become an integral part of the soldier's uniform leading to pervasive information processing on the battlefield and thereby enhancing situational awareness and reducing casualties in combat.

7.4.1 Soft Interconnects in Textile Structures

While the interconnection technology developed and discussed in Chapter 4 was groundbreaking and led to the seamless routing of information in a fabric and the concept of a Wearable Motherboard, the interconnects were "hard." This means the information routes were determined *a priori* in the fabric. The ability to route information “on the fly” would represent a significant enhancement of the interconnect concept in a fabric and therefore, research was directed at creating “soft, programmable” interconnects by integrating an FPGA (field programmable gate array) into a fabric. In doing so, information from one or more sensors can be routed in real-time to desired points in the fabric. Such a capability will result in having “back-up” or redundant data paths if the garment were damaged in use.

7.4.2 Definition and Realization of the Fabric Infrastructure

Figure 7-20 shows the architecture of the fabric infrastructure. The fabric consists of typical cotton yarns (shown in yellow) and conductive yarns as data buses (shown in color) for carrying the information through the fabric. Figure 7-21 shows the loom set-up for weaving the fabric and realizing PMIP. The fabric specifications are shown in Table 7-4.

Table 7-4. Specifications for the Infrastructure for the In-Fabric Network for PMIP

Base Fabric	Fiber Type	100% Cotton
	Yarn Count	30s Ne, 3 ply
	EPI/PPI	32/32
Data bus	Fiber Type	Copper
	Yarn Count	26 AWG
	EPI/PPI	10/10
Manufacturing Technology	Weaving	

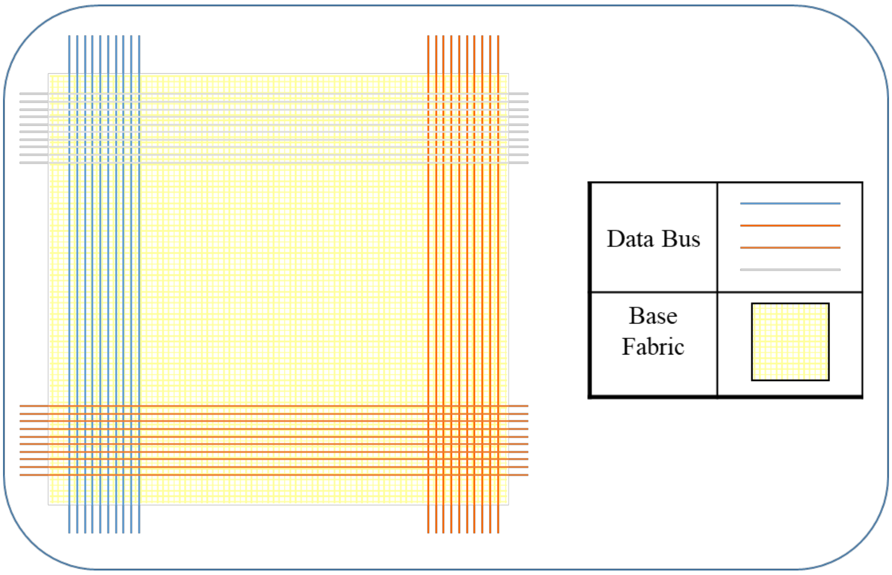


Figure 7-20. Architecture of the Fabric Infrastructure for Personalized Mobile Information Processing.

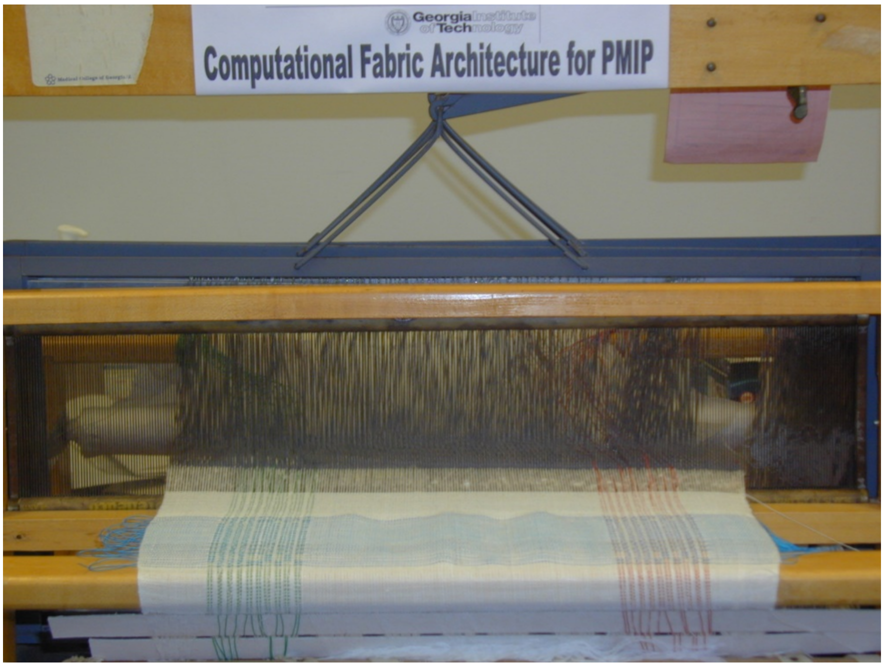


Figure 7-21. Loom for the Realization of Computational Fabric for PMIP

7.4.3 Integration of FPGA into the Fabric Infrastructure

The next step in creating the computational fabric is to integrate the FPGA into the fabric. In the electronics industry, pin connectors are used to mount daughterboards onto motherboards; this technique is both robust and reliable. So, the use of pin connectors for integrating the FPGA into the woven fabric was explored. Figure 7-22 shows a pin connector – also known as an insulation displacement connector – on the right before its integration into the fabric shown on the left. The conductive fibers are treated as the wiring resources in an FPGA to which switching components can be added at desired locations in the fabric. This method of using pin connectors will provide a great deal of flexibility in attaching the type of information processing device to the connector for the desired activity. Because of the modularity, different types of processors can be used with the same wearable information infrastructure. Thus, the user can “plug” in the desired processor/sensor into the fabric and treat the computational fabric as a true “motherboard.” The fabric with the integrated pin connectors can be laundered after removing the plugged-in electronic components further enhancing its use in creating a wearable sensor network.

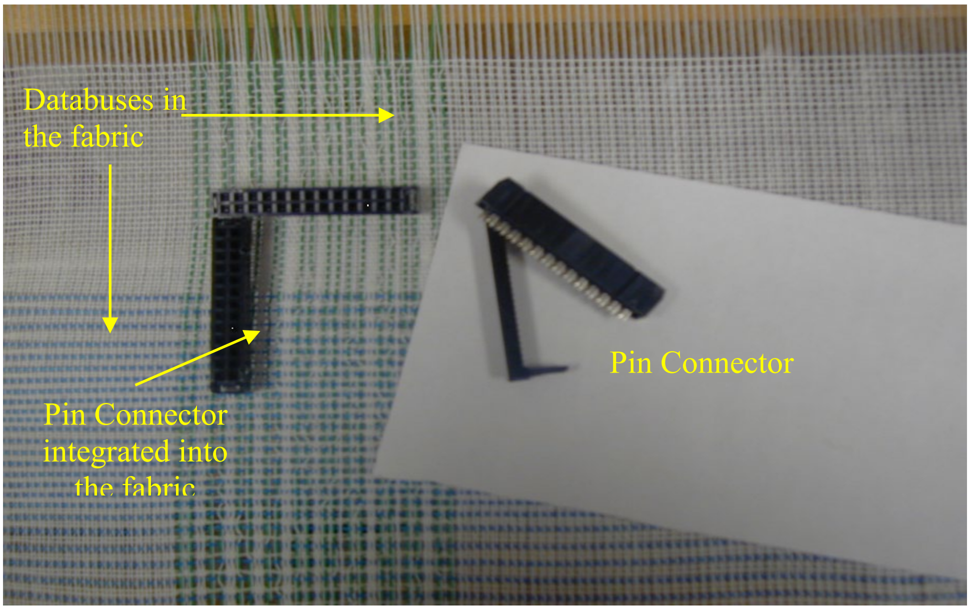
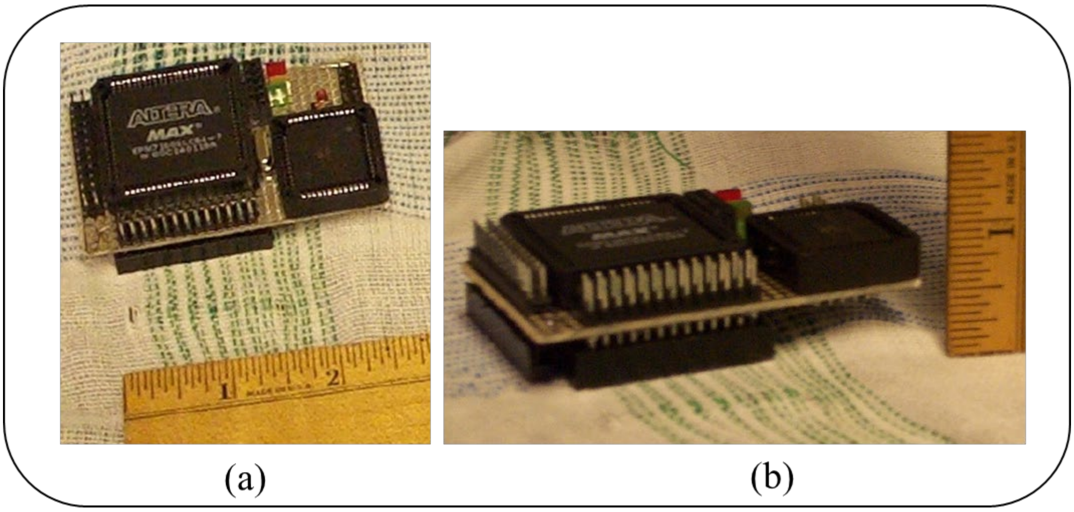


Figure 7-22. Integration of Pin Connectors into the Data buses in the Fabric

The prototype device chosen for integration into the fabric is a 2.8"x1.8" proto-board containing a small EEPROM-based FPGA (Altera EPM7160S) plus a microcontroller (Motorola HC11) as shown in Figure 7-23. The board connects to the fabric using the pin connectors integrated into the fabric.



(a) (b)

Figure 7-23. FPGA on a Fabric

(a) Prototype board with FPGA and daughterboard
(b) Side view: Pin connectors contacting conductive fibers (in color) in the fabric.

Figure 7-24 shows additional FPGAs integrated into the fabric resulting in an in-fabric network for information processing. One of the FPGAs communicated with an external agent (a Linux-based computer) that was responsible for managing the global configuration of the FPGAs in the fabric [72].

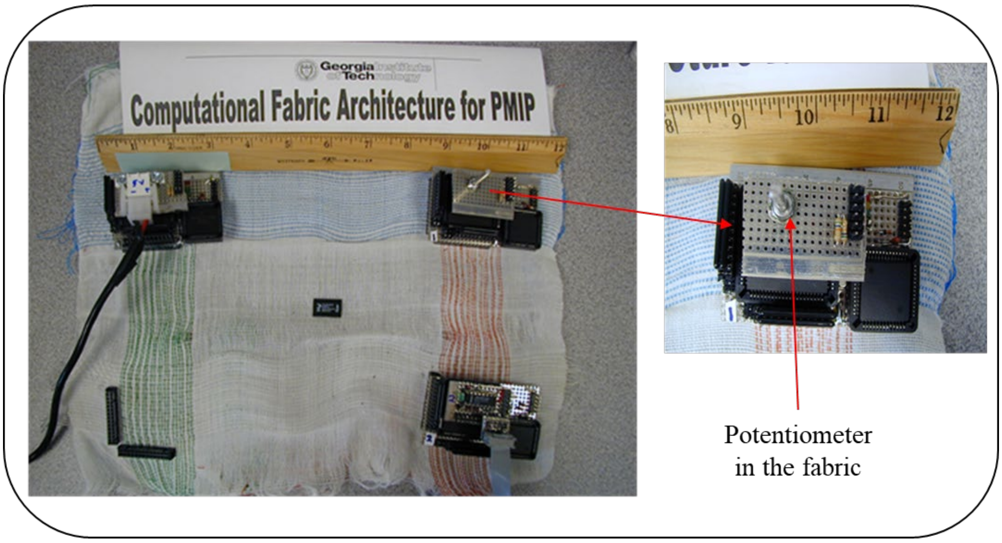


Figure 7-24. An In-fabric Network for PMIP

7.4.4 Realization of the In-Fabric Network for PMIP

To demonstrate the flow and regulation of information in the fabric network through the soft interconnects, a potentiometer has been integrated as a daughterboard into one of the FPGAs as shown in Figure 7-24. As the potentiometer is “twiddled,” the information flow changes; the signal reflecting this change is displayed on the screen in Figure 7-25.

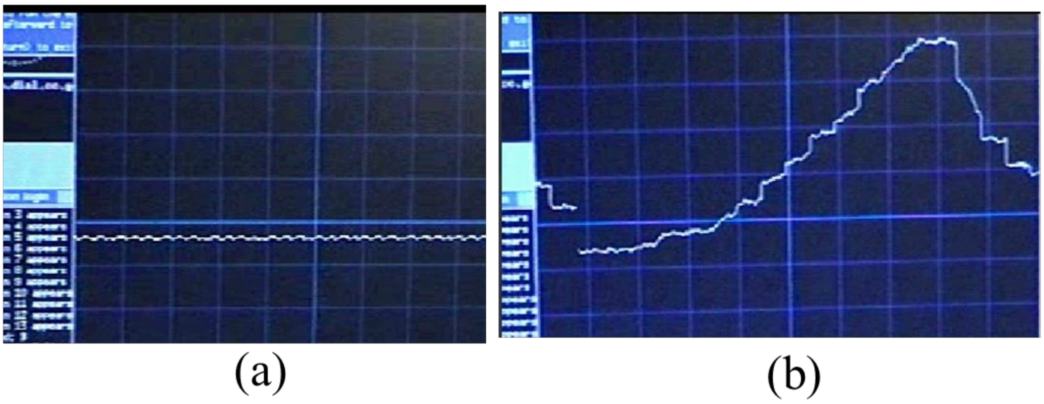


Figure 7-25. An In-fabric Network showing information flow in real-time.

(a) Signal in steady state
(b) Signal follows the twiddling of the potentiometer illustrating the flow and regulation of information through the in-fabric network

Thus, an in-fabric network using FPGAs has been successfully created to realize the concept of a computational fabric.

7.5 Potential of the Wearable Motherboard Paradigm: Adaptive and Responsive Textile Structures (ARTS)

The Smart Shirt – being a garment – is user-centric. In addition to the three application examples presented in the preceding sections, the applications of the technology are limited only by imagination and economics. By serving as a "platform" for a suite of sensors that can monitor an individual unobtrusively, the Smart Shirt technology opens up exciting opportunities to develop "adaptive and responsive" systems that can "think" and "act" based on the user's condition, stimuli and environment [59]. Thus, the rich vital signs data stream (and resulting knowledge) from the Smart Shirt can be used to design and implement "real-time" feedback mechanisms to enhance the quality of care for the individual by providing appropriate and timely medical "intervention." For example, by harnessing advancements in MEMS (micro-electro mechanical systems) technology, a feedback system – including a drug delivery system – can be integrated into the Smart Shirt to prevent fatalities from an anaphylaxis reaction or a diabetes shock. Of course, mechanisms to guard against inadvertent administration of the drug must be built into the control system. Having such a feedback system as an "integral" part of the fabric will represent yet another step towards the realization of the "fabric is the computer" paradigm.

7.6 Research Outcomes

This facet of the research has led to defining the requirements of a wearable sensor network and has demonstrated the role of textiles and clothing in meeting these requirements. The three real-world application examples have successfully demonstrated the versatility of the design and development methodology and the value of the Wearable Motherboard paradigm as a platform for personalized mobile information processing. Thus, the Wearable Motherboard fulfills the role of being a flexible information infrastructure that will facilitate the paradigm of ubiquitous or pervasive computing. This "fabric is the computer" paradigm also demonstrates the feasibility of realizing personalized mobile information processing (PMIP) and sets the stage for the next generation of adaptive and responsive textile structures.

CHAPTER 8

Textiles as a Meta-Wearable: The Next Generation

In this Chapter, we highlight the importance of continuous physiological monitoring and the challenges associated with the use of gel-based sensors in continous monitoring of heart rate and electrocardiogram. We discuss the design and development of a fabric-based sensor, which then leads to the concept of a garment as a sensor. We develop the paradigm of textiles as a meta-wearable and demonstrate how this research has led to its successful realization. We discuss its role as a bridging catalyst between the Internet of Things (IoT) and the Internet of People (IoP). Finally, we present the vision for the field of *i*-Textiles – or interactive textiles – resulting from this research and discuss the various building blocks associated with this vision.

8.1 Cardiovascular Diseases and Need for Continuous Monitoring of Vital Signs

Heart disease is the leading cause of death for both men and women in the United States. According to the CDC, 630,000 Americans die from heart disease each year – that is one in every four deaths [73]. In the United States, someone has a heart attack every 40 seconds. Each minute, more than one person in the United States dies from a heart disease-related event. Heart disease costs the United States about $200 billion each year, which includes the cost of health care services, medications, and lost productivity. Thus, an individual with a cardiovascular disease would greatly benefit by continuous monitoring of the heart's electrical activity, typically captured in an electrocardiogram (EKG).

8.1.1 Gel-Based Sensors for Continuous Monitoring

For continuous monitoring, an at-risk patient is advised to use a holter monitor by the physician. A holter monitor is a battery-operated portable device that measures and records the patient's activity (EKG) continuously for 24 to 48 hours or longer [74]. The device is the size of a small camera. It has wires with silver dollar-sized electrodes that attach to the patient's skin. The results from the monitor are analyzed by the physician in the office to determine the necessary intervention for the patient, viz., medication, angioplasty, insertion of a pacemaker, or bypass surgery.

The conventional EKG electrode has a conductive gel (silver-silver chloride) and an adhesive backing to affix the conductive lead to the patient's skin. Since the electrode sticks to the body, it is difficult to remove; it can also cause skin irritation when used continuously for extended periods of time, e.g., when using a holter monitor. Therefore, for continuous monitoring, it is important to deploy sensors that do not have these shortcomings. Since clothing is the first layer in contact with the patient, its potential to function as a sensor and acquire the electrical signals from the patient's body has been investigated.

8.2 Design and Development of Fabric-based Sensors

8.2.1 Conductive Yarns: Replacement for Silver-Silver Chloride Electrolyte in Sensor

Conductive yarns have been knitted to create the stand-alone sensor shown in Figure 8-1. The conductive yarns in the sensor act as the silver-silver chloride electrolyte in the commercial EKG sensor. The specifications are shown in Table 8-1. A T-Connector has been attached to the knitted sensor using conductive epoxy paste discussed in Chapter 4. The T-Connector is designed to "plug" the fabric-based sensor into the Wearable Motherboard to monitor vital signs.

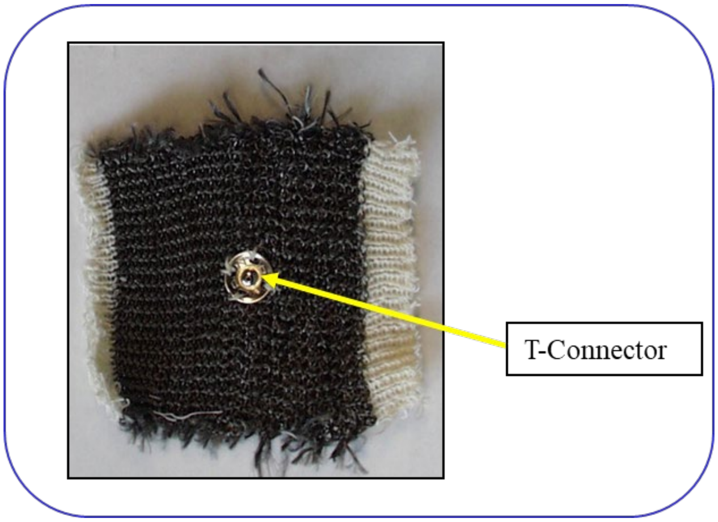


Figure 8-1. Knitted Fabric Sensor

Table 8-1. Specifications of the Knitted Fabric Sensor

Knitted Fabric Sensor	
Yarn Material	Uninsulated 100% Stainless Steel
Yarn Count	2250 Denier
Fabric Structure	1x1 Rib
Fabric Density	16 wales/inch and 18 courses/inch
Sensor Size	1.5" x 1.5"
Sensor Weight	12 oz/yd^2

Conductive yarns have then been woven to create a woven version of the fabric sensor; this is shown in Figure 8-2. The specifications are shown in Table 8-2.

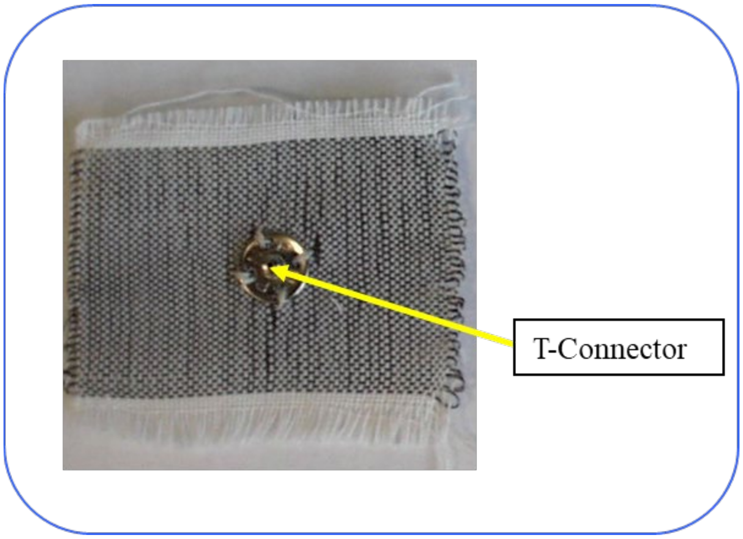


Figure 8-2. Woven Fabric Sensor

Table 8-2. Specifications of the Woven Fabric Sensor

Woven Fabric Sensor	
Warp Yarn	Cotton
Warp Yarn Count	18s Ne
Filling Yarn	Uninsulated 100% Stainless Steel
Filling Yarn Count	2250 Denier
Fabric Structure	1x1 Plain
Fabric Density	30 ends/inch and 22 picks/inch
Sensor Size	1.5” x 1.5”
Sensor Weight	7.5 oz/yd^2

8.2.2 Monitoring EKG with the Fabric Sensors

The knitted fabric sensors were plugged into the medical version of the Smart Shirt shown earlier in Figure 7-7. The subject wore the garment and positioned the sensors on the body. The Spandex (Lycra®) integrated into the Smart Shirt ensures that the sensors are held in close contact with the body to obtain signals and maintain their fidelity. Using the external T-Connectors, the Smart Shirt was connected to the Dynamap monitor and the EKG was measured – see EKG trace in Figure 8-3. Similar tests have been successfully carried out with the woven version of the sensor.

Figure 8-3. EKG Trace using the Knitted and Woven Fabric Sensors plugged into the Wearable Motherboard

8.2.3 Advantages of Fabric-based Sensors

This new sensor pioneers the concept of a fabric-based sensor that can monitor the vital signs of the wearer. It eliminates the need for rubberized sensors or gel-based sensors both of which can cause rashes, be difficult to apply and take-off, especially if the skin is very sensitive (newborns, firefighters, senior citizens, acute care patients, post-operative recovery, etc.). When plugged into the Wearable Motherboard, it creates a comfortable and "natural" system for monitoring vital signs. Additionally and alternatively, it can replace the existing sensors (rubberized and/or gel-based) in other monitoring equipment. Thus, the fabric-based sensor overcomes the shortcomings of traditional EKG sensors and thereby paves the path for their use in continuous monitoring of individuals, especially those with cardiovascular diseases.

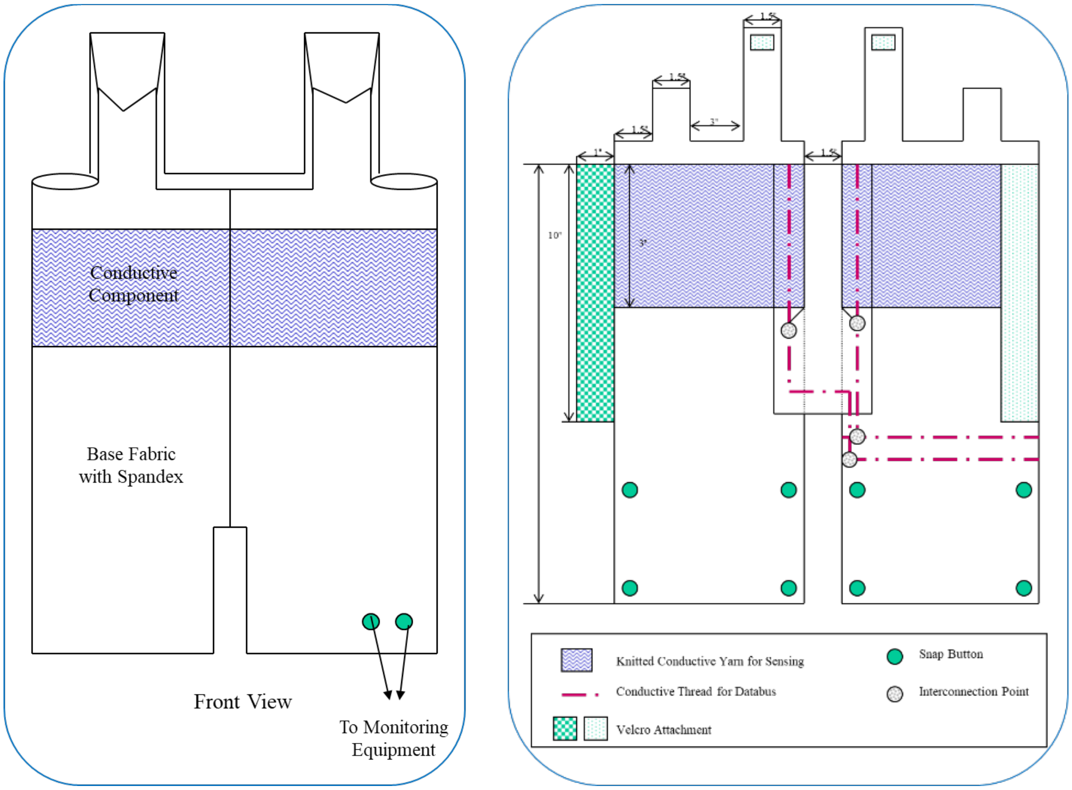
Yet another advantage of this new sensor is that the conducting fibers can also be used to transmit information "to" the wearer, i.e., facilitate bi-directional communication. Such a capability will be valuable when monitoring babies prone to SIDS. Typically, when the baby stops breathing, the caregiver manually intervenes to activate (e.g., move, pat) the child. One possibility is to send a mild electrical impulse, which can stimulate the baby and automate the intervention to trigger breathing. Additional research must be carried out to investigate this functionality of fabric-based sensors in conjunction with the Wearable Motherboard's information-transmitting capabilities.

8.3 Garment as a Sensor

The next step has been to investigate the possibility of making the fabric sensor an "integral" part of the underlying garment during the production process, i.e., exploring the paradigm of "garment is the sensor."

8.3.1 Initial Prototype

The design and development methodology in Chapter 4 has once again been instantiated to create a prototype of the Wearable Motherboard with built-in sensors. Figure 8-4 shows two views of the garment with integrated sensors produced using a flatbed knitting machine in the lab.



(a) (b)

Figure 8-4. Architecture of Garment as a Sensor

(a) Front View
(b) Opened-out view with details of the structure

The conductive yarn is uninsulated silver-doped nylon and the base fabric consists of cotton with Spandex to create a form-fitting garment. Figure 8-4 also shows the architecture of the conductive buses, the interconnection points, and snap buttons for closure. The T-Connectors on the outside of the garment connect to monitoring equipment to measure the EKG. To facilitate easy donning and doffing of the garment, Velcro® closure has been incorporated at the top as shown in the figure. Two views of the resulting garment are shown in Figure 8-5. The EKG has been successfully recorded with the prototype thus illustrating the realization of a garment with integrated sensors for monitoring vital signs [75].

Figure 8-5. Garment as a Sensor: Initial Prototype

8.3.2 The Advanced Prototype with Precise Positioning of Sensors

Once the concept of a garment with integrated sensors was realized, the next step has been to create a garment with the sensors placed in the desired or specific locations while being an integral part of the fabric. The use of Intarsia knitting technique [76] has been investigated for this purpose. Intarsia is typically used to create specific “blocks” or designs in desired locations in the fabric during the knitting process with yarns that are different from the base fabric yarn. This concept was deemed to be ideal for creating sensors using conductive yarns in specific locations in the fabric based on the architecture in Figure 7-6.

The specifications for the advanced prototype with integrated sensors and data buses in the garment are shown in Table 8-3.

Table 8-3. Specifications of Garment with Integrated Sensors

Base Fabric Yarns	Nylon 70D/68F 1 ply and Covered Yarn Spandex/Nylon 40D/70D 1 Ply
Integrated Sensor	Silver-doped Nylon, 1 ply, covered Yarn Spandex
Data bus	Insulated Stainless Steel
Manufacturing Technology	Knitting

The samples have been knitted on a Shima-Seiki knitting machine using Intarsia technique. The resulting fabric with integrated sensors is shown in Figure 8-6. The outer view of the fabric is shown on the left of the figure; the sensors integrated into the fabric during knitting are shown on the right with the inset showing a close-up of the sensor. The data buses have also been integrated into the fabric during knitting.

Figure 8-6. Fabric with Integrated Sensors and Data buses

The front and back pieces have been sewn together to create the garment shown in Figure 8-7. The left side of the figure shows the outer view of the garment with the plugged-in multifunction processor for collecting, processing, and transmitting information from the various sensors to an external device (e.g., monitoring equipment, laptop) for additional processing and action. The various sensors integrated into the fabric during knitting are shown on the right side of the figure. The figure also shows the conductive data buses integrated into the structure. The finished garment is similar in look and feel to that of a typical T-shirt.

The garment was worn by a subject and the resulting EKG plot is shown in Figure 8-8 thereby demonstrating the successful working of the Smart Shirt with built-in sensors and data buses. By having a technology that is not only ubiquitous (in the form of clothing) but also has the ability to respond to the changes in the needs of the wearer (e.g., the three scenarios discussed earlier in Section 7.1.1), the quality of preventative care can be significantly enhanced, further reinforcing the paradigm that "investment in prevention is significantly less than the cost of treatment."

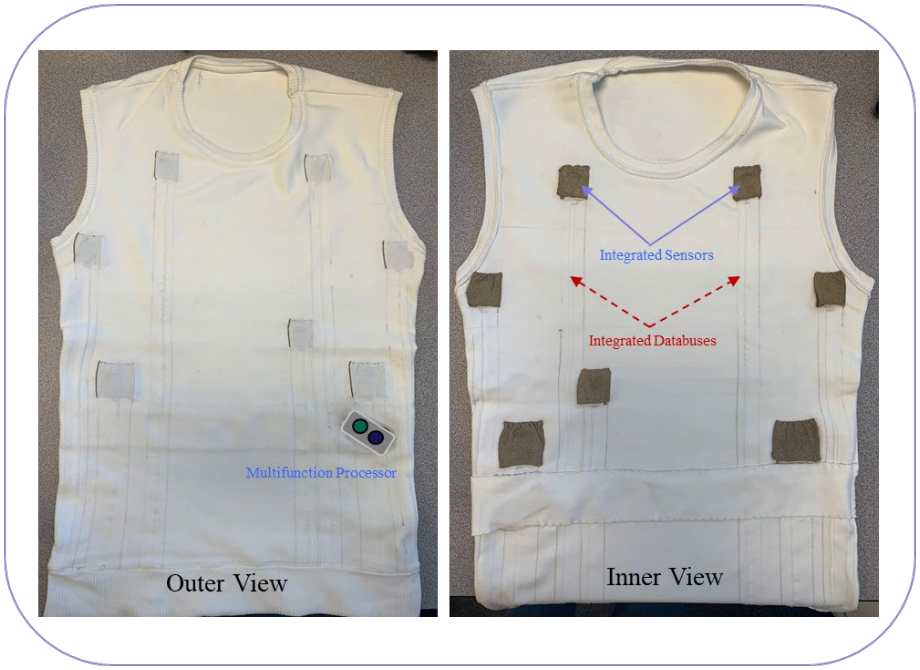


Figure 8-7. Garment as a Sensor: Outer and Inside Views with Integrated Sensors and Data buses

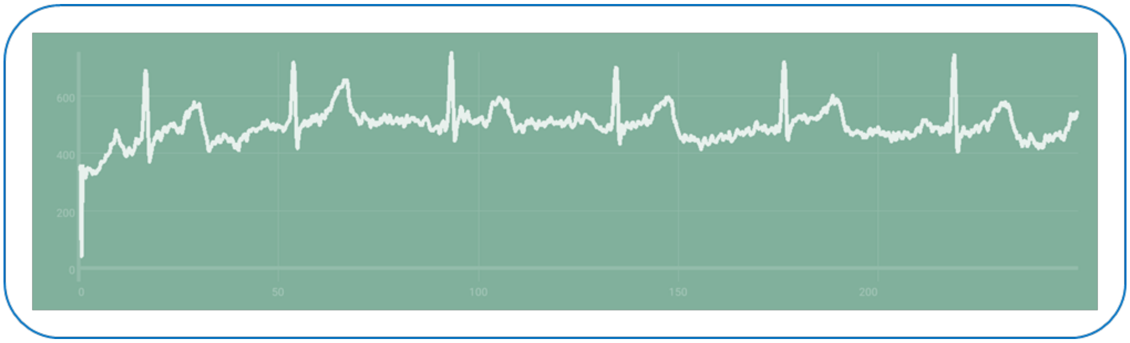


Figure 8-8. An EKG plot from the Advanced Prototype with Integrated Sensors

8.4 The Paradigm of Meta-Wearable

The development of the Wearable Motherboard with integrated sensors has resulted in a platform that has the physical form factor of a garment, integrated sensors for monitoring electrical signals from the wearer's body, and an integrated information infrastructure in the form of conductive data buses for transmitting information from the sensors (both built-in and plugged-in) to external devices (e.g., monitoring equipment, the Cloud). We now explore the paradigm of the Wearable Motherboard as a meta-wearable.

8.4.1 The Wearable Motherboard: A Meta-Wearable

In Section 7.1.6, the attributes of textiles in meeting the requirements of a wearable sensor network (discussed in Section 7.1.4) were presented. Figure 8-9 shows a structured representation of the physical and functional attributes of the Wearable Motherboard realized in this research [77]. It is lightweight, aesthetically pleasing (because yarns of various colors and types can be used to enhance the aesthetics of the garment), and it is shape conformable like any textile structure. From a functional standpoint, it can be configured to perform a range of monitoring and information processing activities enhancing its versatility and responsiveness.

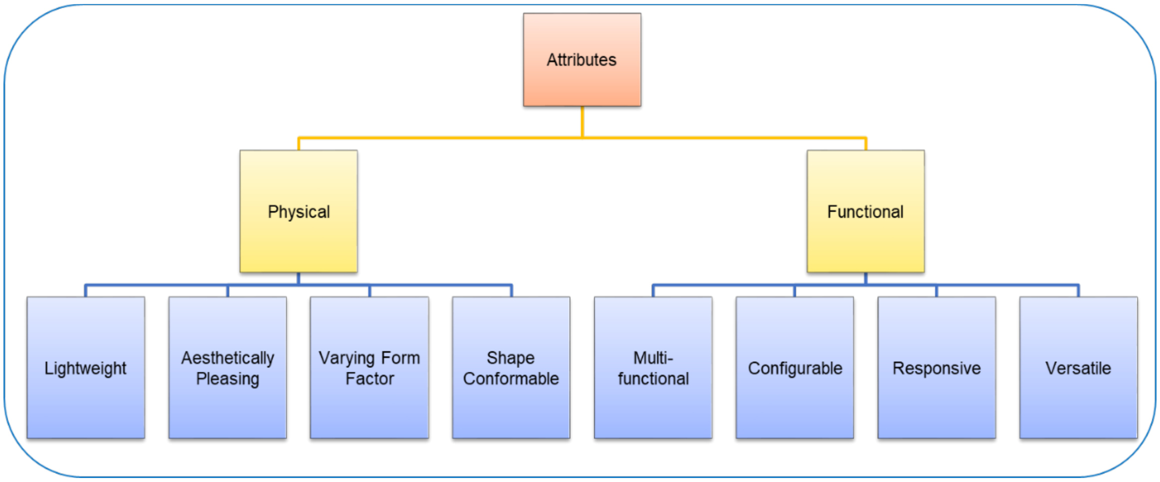


Figure 8-9. Attributes of the Wearable Motherboard (Smart Shirt)

Figure 8-10 shows the architecture of the Wearable Motherboard (Figure 6-18) overlaid on the garment in Figure 8-7. As seen in the figure, there are two types of sensors – sensors that are integrated into the structure and those that can be plugged-in, e.g., temperature and microphone, using the T-Connectors in the garment. The data buses integrated into the garment serve as communications pathways for the sensors and processors and provide the necessary bandwidth for interactivity. The topology, or structure of placement of these data buses, can be engineered to suit the desired sensor surface distribution profile during manufacturing, making it a versatile technology platform for plugging in different types of sensors.

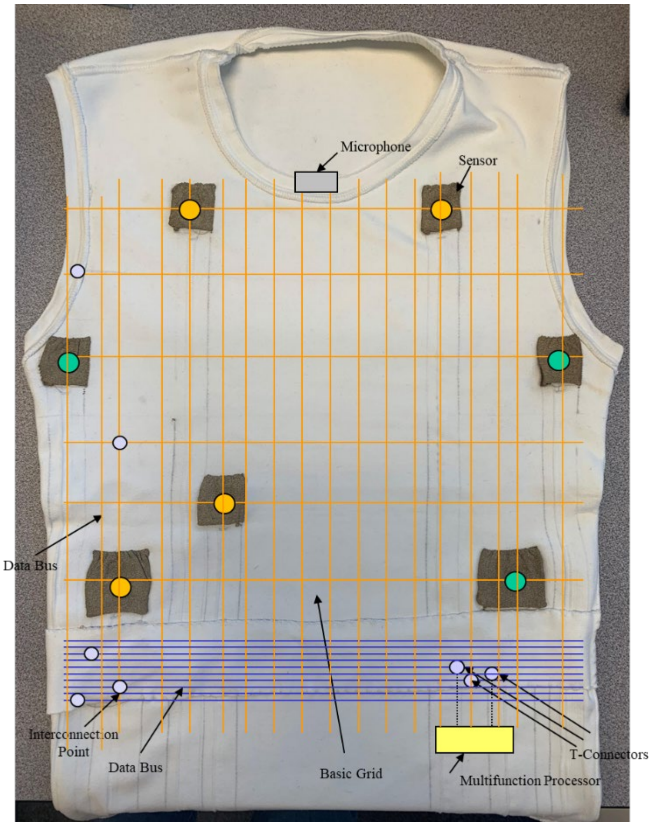


Figure 8-10. The Paradigm of Meta-Wearable: Wearable Motherboard Architecture Overlaid on Garment with Integrated Sensors and Data buses

Thus, these capabilities make the Wearable Motherboard a meta-wearable because the garment can serve as a "sensor" in its own right and act as a host or information infrastructure (or motherboard) for carrying information from and to the wearer through the garment. Therefore, from a performance perspective, a textile fabric (or clothing) is a true meta-wearable making it a versatile platform for the incorporation of sensors and processors to harness situational awareness data while retaining its aesthetic and comfort attributes, among many other textile-unique properties.

8.4.2 Meta-Wearable of Textiles and Big Data

In today's harried world, an individual is likely to be forgetful and leave a personal electronic device behind (say, the smartphone), but is unlikely to walk out of the home without clothes! This is, therefore, yet another compelling reason to use textiles or clothing as the infrastructure or meta-wearable for harnessing data from the individual [78]. Moreover, since clothing is always "on" the individual, it provides real-time data that can be traced back to the source, thus effectively addressing the four dimensions of big data shown in Figure 8-11.

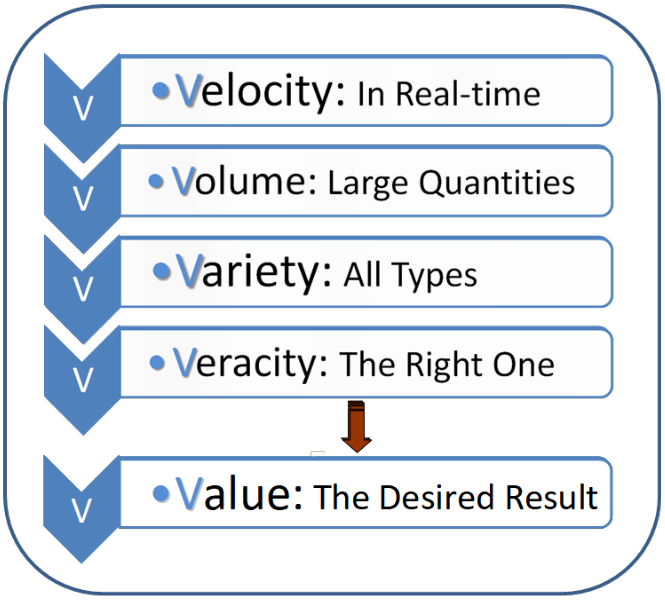


Figure 8-11. The Attributes or Dimensions of Big Data and Delivering Value

Big data refers to large amounts and varieties of fast-moving data (structured and unstructured) from individuals and groups that can be processed, analyzed and integrated over extended periods of time. As shown in the figure, this creates significant value since it reveals new insights into human behavior and activities. At the heart of the concept of big data is the individual who is both the source of the data and the recipient of the resulting value after the processing/harnessing of the data. In other words, the human is the information node and also becomes the target “market of one” receiving a unique solution or benefit from the data.

8.4.3 Integrating the Internet of Things and the Internet of People

With the recent advancements in materials, electronics, communications and manufacturing technologies, the meta-wearable of textiles is increasingly becoming a viable platform for harnessing big data. Intelligent sensors with communications capabilities are being embedded into everyday physical objects (e.g., automobiles, medical devices, and consumer electronics); these objects can be easily networked and accessed over the Internet and the paradigm of the Internet of Things (IoT) is becoming ubiquitous. Similarly, the compact and powerful personal electronic devices such as smartphones are enabling connectivity amongst people giving rise to the paradigm of Internet of People (IoP). Both IoT and IoP are generating huge amounts of heterogeneous data in real-time, i.e., big data. These personal electronic devices are typically worn or embedded in the clothing of individuals thus putting textiles at the heart of IoT and IoP as shown in Figure 8-12.

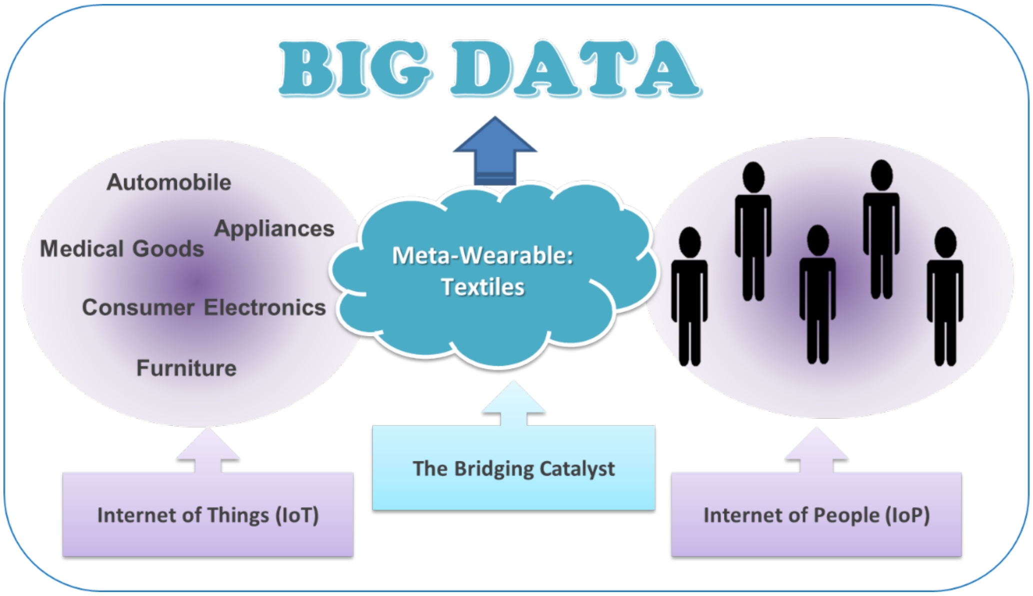


Figure 8-12. Textiles and Clothing: The Bridge between IoT and IoP

Textiles play the critical role of the bridging catalyst to harness this big data by easily interacting with both the intelligent physical objects in IoT and the people in IoP. Thus, the meta-wearable of textiles is powering today's wearables revolution [78]. As discussed in Chapter 1, the Jacquard loom proved to be the inspiration for Charles Babbage's Analytical Engine, which eventually led to von Neumann's architecture of a stored program computer, the basis for present day computers. Figure 8-13 shows this lineage.

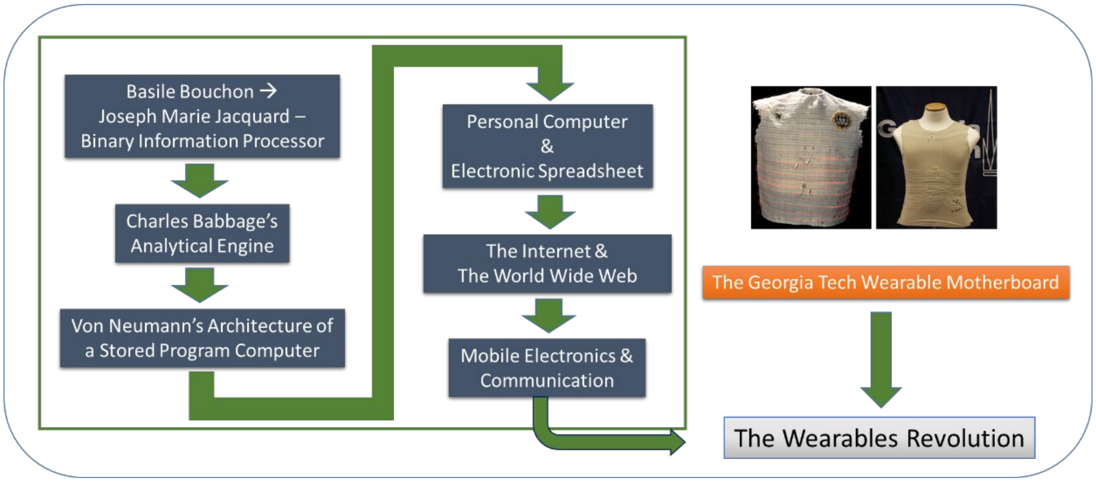


Figure 8-13. The Emergence of the Wearables Revolution: The Textile Lineage

The proliferation of personal computers was catalyzed by the development of the first electronic spreadsheet VisiCalc®, which brought computing to the masses and furthered the computer revolution [79]. The birth of the internet and the subsequent creation of the World Wide Web were the next major milestones that significantly transformed information processing [80]. Subsequently, the advent of inexpensive electronics and mobile communications devices (e.g., smartphone) made "information processing on the go" a ubiquitous reality as shown in Figure 8-13.

The successful development of the Wearable Motherboard has resulted in a flexible information infrastructure – a wearable sensor network – in the form of an easy-to-use, comfortable, and natural garment. Just as its predecessors ranging from James Kay to Joseph-Marie Jacquard sparked revolutions in their own way, the textile-based Wearable Motherboard has pioneered the wearables revolution being witnessed today and this is shown in Figure 8-13.

8.5 The Field of *i*-Textiles

The development of the Wearable Motherboard, which pioneered the integration of electronics with traditional textiles, gave birth to the field of "electronic or e-textiles" to represent this new class of textile structures with functional capabilities. However, as the research progressed, it became clear that "e-textiles" did not convey the "interactivity" that is key to the successful development and deployment of such structures. Therefore, the term "*i*-Textiles" or interactive textiles has been proposed to convey this "dynamic" or "interactive" nature of structures that goes beyond just the integration of electronic elements into textile structures [61]. It is not just the substitution of the word "interactive" for "electronic." Rather, it is a fundamental shift with respect to these structures that calls for going beyond the simple incorporation of electronic devices on to the fabric – the fabric does indeed become the computer eventually (fabric is the computer) – making it a truly adaptive and responsive textile structure [59]. The user-wearable symbiosis and dynamics open up new research frontiers at the intersection of materials, information technologies, and human factors.

8.5.1 The *i*-Textiles Vision

Figure 8-14 depicts the vision for "*i*-Textiles" or interactive textiles embodying the paradigm of "fabric is the computer." We will now discuss the various "building blocks" in light of the research carried out in this dissertation and the need for their seamless integration to realize the vision.

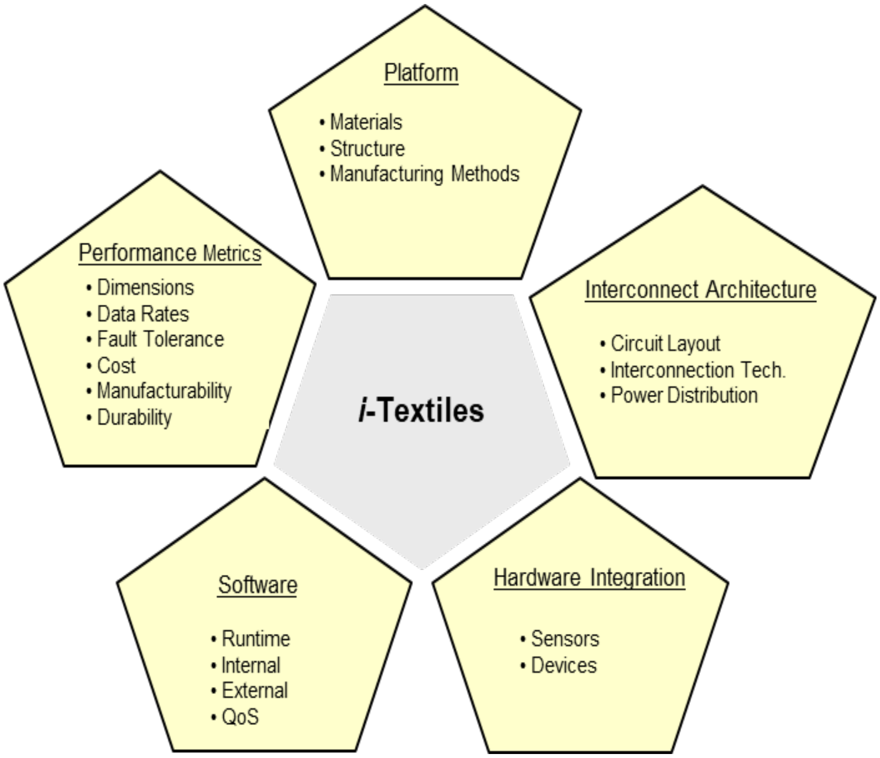


Figure 8-14. The *i*-Textiles Vision

The physical fabric or Platform is the foundation of *i*-Textiles shown in Figure 8-14. Its design and development involve the exploration of materials, structures and manufacturing technologies as represented in Figure 2-2 and successfully realized on this research through the various instantiations of the Wearable Motherboard discussed in previous chapters. 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 (Figure 4-1) and interconnection technologies, i.e., the realization of "textile electrical circuits." Interactivity requires sensors, processors, and communication and control, among others for any application –

from monitoring patients prone to pressure ulcers in hospitals [81] to monitoring soldiers in battlefields. Therefore, Hardware Integration constitutes the third facet or building block shown in Figure 8-14.

The successful integration of sensors and processors has been accomplished on this research as discussed in this and in previous chapters. Issues related to information processing such as fault tolerance in light of manufacturing defects and Quality of Service (QoS) are critical for the incorporation and optimal utilization of computing resources, and therefore, "Software" is the fourth facet of *i*-Textiles vision. Finally, as shown in the figure, a set of underlying performance metrics ranging from the physical dimensions (of the resulting structure/system) to costs, manufacturability and data flow rates are relevant to assessing the successful realization and performance of desired *i*-Textiles. 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, materials, sensing, computing and communications technologies and application domains, such as medicine, space, military, and information processing, to name a few.

8.6 Research Outcomes

This facet of the research has led to the successful design and development of fabric-based sensors that address the shortcomings of gel-based and rubberized sensors currently used for long-term monitoring of individuals, especially those with cardiovascular diseases. These novel sensors also facilitate bi-directional communication, i.e., transmission of signals from and to the wearer. Another important outcome is the realization of the Wearable Motherboard with integrated sensors in the form of an easy-to-use, comfortable, and customizable garment for monitoring the vital signs of individuals in a wide array of applications. This development has served as a precursor for today's "wearables revolution" exemplified by the proliferation of fitness trackers and smart watches. The concept of textiles as a meta-wearable has been proposed. The development of the Wearable Motherboard with integrated sensors and information infrastructure represents the successful realization of the meta-wearable paradigm. It is the bridging catalyst between the Internet of Things (IoT) and the Internet of People (IoP). The research has led to the birth of the field of e-textiles and has subsequently led to defining the vision for the field of interactive or *i*-textiles. The advancements made on the various building blocks during the course of this research have brought this exciting vision closer to reality.

CHAPTER 9

Conclusions and Recommendations

The two specific aims of the research have been to:

- Create a textile-based information infrastructure: The Wearable Motherboard; and
- Demonstrate the versatility of the Wearable Motherboard paradigm through applications and develop the concept of textiles as a meta-wearable.

Based on the research carried out and discussed in the preceding chapters, the following conclusions can be drawn to demonstrate the successful realization of the twin aims:

In Chapter 2, a methodology for product design and development in a concurrent engineering environment has been proposed. In this methodology, customer requirements are translated into appropriate properties that the textile structure must possess to fulfill the requirements. The Properties lead to the specific design for the textile structure. These Properties in the Design are achieved through the appropriate choice of Materials & Fabrication Technologies by applying the corresponding design parameters. All these major facets in the proposed framework are linked together and help the product design team make the logical progression from general ideas to specific parameters and instantiations in a product family. In and of itself, the design and development framework resulting from this research represents a significant contribution to systematizing the process of designing textile structures and systems for a multitude of applications. The textile/apparel industry can adopt this framework for product design in a concurrent engineering environment and become successful in the context of today's dramatically decreasing concept-to-market timeframe and the highly competitive global marketplace.

In Chapter 3, a novel technology for creating a full-fashioned woven garment on a loom has been developed, which represents a pioneering contribution to textile engineering. This technology has then been used to integrate a plastic optical fiber (POF) into the structure during the fabric production process without any discontinuities at the armhole or the seams. This innovative weaving concept has then been enhanced to create garments with sleeves on the loom. A material and method to protect the cladding of the POF during its handling in processing has been developed and successfully implemented to maintain the integrity of the optical fibers in the structure.

In Chapter 4, the novel concept of "interconnections" in a textile structure has been proposed to seamlessly route information from sensors or devices in any part of the fabric to another through the yarns in the fabric thus creating a flexible textile-based information infrastructure analogous to the traditional printed circuit board (PCB). An interconnection technology has then been developed and successfully used to create interconnects or electrical junctions in textile structures. The concept of Textillography for automating the creation of large-scale interconnects in textile structures has been proposed and defined.

In Chapter 5, a fundamental understanding of the performance of conductive yarns to serve as an information infrastructure component for the Sensate Liner has been developed and this has led to the selection of conductive fibers for the Sensate Liner.

In Chapter 6, the design and development methodology has been used to create a Sensate Liner for combat casualty care. The elegance of the design of the

Sensate Liner lies in the fact that the various building blocks can be put together (like LEGO® blocks) in any desired combination to produce structures to meet specific end-use requirements. The major building blocks of technology have been successfully integrated to create woven and knitted versions of the Sensate Liner. The novel concept of a "Wearable Motherboard" has been proposed. The Wearable Motherboard is a fabric-based information infrastructure, which serves as a flexible and wearable framework into which sensors and devices can be plugged making it similar to a motherboard in an electronic device. This represents true convergence between electronics and textiles giving birth to the new field of electronic or "e-textiles." The modular architecture of the Wearable Motherboard enables the user to control the degree of convergence based on the desired application.

In Chapter 7, three typical scenarios involving information processing activities have been used to identify the need for a wearable sensor network and define the key requirements of such a network. The unique role of textiles and clothing in meeting these requirements and serving as a platform has been analyzed. Real-world instantiations of the Wearable Motherboard – for physiological monitoring (medical, sports, and infants) and in-fabric information processing network – successfully demonstrated the versatility of the design and development methodology; they have also established the value of the Wearable Motherboard as a platform for personalized mobile information processing and laid the foundation for the next generation of adaptive and responsive textile structures.

In Chapter 8, the need for continuous monitoring of individuals has been established using the example of cardiovascular diseases, the number one cause of deaths in the United State. Fabric-based sensors have been designed, produced, and successfully tested to address the shortcomings of gel-based sensors currently used for physiological monitoring. These novel sensors also facilitate bi-directional communication, i.e., transmission of signals from and to the wearer further enhancing the capabilities of the fabric-based monitoring system. The next generation of the Wearable Motherboard with integrated sensors and data buses – in the form of an easy-to-use, comfortable, and customizable garment – has been developed and successfully tested. The concept of textiles as a meta-wearable has been proposed. The next generation Wearable Motherboard with integrated sensors and information infrastructure represents the successful realization of the meta-wearable paradigm. It is the bridging catalyst between the Internet of Things (IoT) and the Internet of People (IoP). The vision for the new field of interactive or *i*-textiles has been defined and the advancements realized on the various building blocks during the course of this research have brought this exciting vision closer to reality as seen in the range of commercial products in the marketplace.

In closing, the field of textiles was responsible not only for the first industrial revolution but also for setting the stage for the information processing revolution with the invention of the Jacquard weaving machine, which served as an inspiration to Charles Babbage for his work on the Analytical Engine. Today, wearable sensor networks – using textiles as the physical and information infrastructure – are bringing about yet another transformation in the field of information processing by harnessing ambient intelligence in a wide variety of real-world applications. Just as the spreadsheet pioneered the field of personal computing that brought “computing to the masses,” it is anticipated that wearable sensor networks – using the Wearable Motherboard and associated concepts and technologies developed in this research and presented in this dissertation – will bring affordable personalized mobile information processing and the power of ambient intelligence to anyone, anywhere at any time and enhance the quality of life for all. Indeed, the latter, viz., enhancing the quality of life, would represent the realization of the ultimate goal of any technology and has been the primary goal of this research.

We now present recommendations for future research to explore novel applications of textiles as a meta-wearable and an information infrastructure for big data analytics.

- The proliferation of textiles with integrated electronic materials presents significant challenges in creating a sustainable supply chain and ecosystem. Research must be carried out to investigate the cost-effective recycling of such interactive textiles.
- There is a critical need for standards in defining what constitutes an interactive textile and the processing techniques associated with creating and using them. The development of such standards should be a collaborative effort between the R&D and manufacturing communities in this area.
- Interactive textiles with integrated sensors and data buses facilitate bi-directional communication. Research must be carried out to investigate this functionality and identify opportunities for the applications of this technology for SIDS, pressure ulcer prevention, and pelvic stimulation to address incontinence, to name a few, and create a truly adaptive and responsive textile system.
- The challenges associated with protection of individual privacy, data security and other social aspects of the acceptance of interactive textiles must be addressed because these meta-wearables are collecting personal information. The electronics and communications industry in collaboration with privacy protection organizations must develop appropriate protocols that will identify proper technology and public policy solutions to further the free acceptance and

use of interactive textiles.

- Apparel manufacturing is a labor-intensive operation whereas electronics manufacturing is highly automated. Consequently, the production rates are much higher in electronics manufacturing. The apparel industry is not as precise in terms of topology and interfaces between the different components when compared to the electronics industry whose operating paradigm is precision. Thus, the differences between these manufacturing paradigms must be explored to facilitate the widespread adoption of interactive textiles.
- Finally, interactive textiles present an unobtrusive and versatile platform for the collection of large amounts of data that meet the characteristics of volume, velocity, variety and veracity associated with big data. The use of these interactive textiles to collect data on usability and comfort must be investigated to lay the foundation for the redesign of equipment such as hospital beds, automobile seats, and wheelchairs.

APPENDIX A

Electrical Properties of Yarns and Fabrics with Woven-in Conductive Fibers

1. Electrical Properties of Conductive Yarn

1.1 Effect of Tensile Strain on Resistance of Stainless Steel Yarn

1.1.1 *Insulated* Stainless Steel Yarn (Material A1)

There is no significant effect of tensile strain on the resistance of insulated stainless steel yarns when the strain is increased from 0% to breaking strain (1.23%) as shown in Table A1-1 and Figure A1-1. Also, at any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated stainless steel yarns as shown in Table A1-2 and Figure A1-2.

Table A1-1 Resistance of Insulated Stainless Steel Yarn at Different Voltage and Tensile Strains

Unit: Ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	17.6997	17.7020	17.6997	17.7000
0.2%	17.7609	17.7633	17.7612	17.7615
0.4%	17.7609	17.7627	17.7608	17.7606
0.6%	17.7695	17.7712	17.7666	17.7664
0.8%	17.7752	17.7778	17.7741	17.7765
1.0%	17.8012	17.8053	17.8031	17.8028
1.2%	17.7177	17.7201	17.7174	17.7188

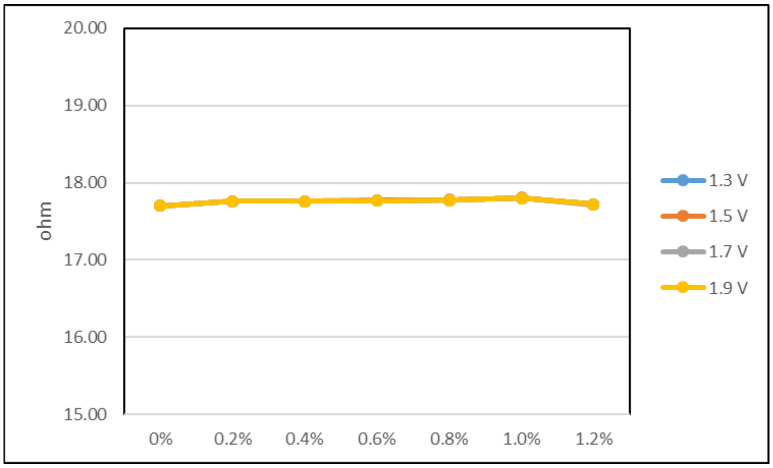


Figure A1-1 Resistance of Insulated Stainless Steel Yarn at different Voltages and Tensile Strains

Table A1-2 Resistance of Insulated Stainless Steel Yarn at Different Frequencies and Tensile Strains

Unit: Ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	17.6448	17.7221	17.7145	17.7081	17.7024	17.7000
0.2%	17.7179	17.7878	17.7831	17.7741	17.7654	17.7615
0.4%	17.6889	17.7780	17.7791	17.7770	17.7657	17.7606
0.6%	17.6632	17.7770	17.7816	17.7718	17.7756	17.7664
0.8%	17.6730	17.7683	17.7700	17.7689	17.7739	17.7765
1.0%	17.7003	17.8026	17.8147	17.8152	17.8039	17.8028
1.2%	17.6505	17.7543	17.7447	17.7334	17.7231	17.7188

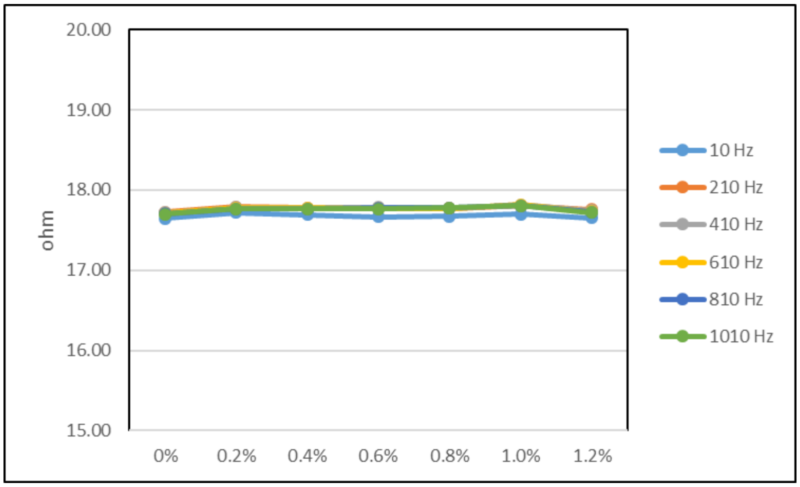


Figure A1-2 Resistance of Insulated Stainless Steel Yarn at different Frequencies and Tensile Strains

1.1.2 *Uninsulated* Stainless Steel Yarn (Material A2)

The resistance of the uninsulated stainless steel yarn doesn't change when the tensile strain changes from 0.2% to 1.2% at different voltages. However, as shown in Figure A1-3, the resistance increases by nearly 5% in the range 1.2% to breaking strain (1.27%). This interesting behavior – in contrast to the insulated yarn – may be attributed to the difference in the modes of deformation of the two yarns. In the case of the uninsulated yarn, the fibrous strands in the yarn may be retaining electrical connectivity – the result of a "non-catastrophic" failure of the yarn – while the insulated yarn is experiencing a catastrophic failure. The former causes "thinning" of the yarn leading to an increase in the resistance, while that phenomenon doesn't occur in the case of the insulated yarn. As shown in Tables A1-3, A1-4 and Figures A1-3, there is no significant effect of frequency and voltage on the resistance of uninsulated stainless steel yarns at any given tensile strain.

Table A1-3 Resistance of Uninsulated Stainless Steel Yarn at Different Voltages and Tensile Strains

Unit: Ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	22.13927	22.14158	22.14109	22.14361
0.2%	23.31204	23.31409	23.31264	23.31399
0.4%	23.33153	23.33405	23.33317	23.33499
0.6%	23.4139	23.41702	23.41684	23.42007
0.8%	23.5584	23.562	23.56222	23.56455
1.0%	23.62454	23.62714	23.62534	23.62634
1.2%	23.67886	23.68143	23.6804	23.68209
1.3%	24.89705	24.89957	24.89706	24.89791

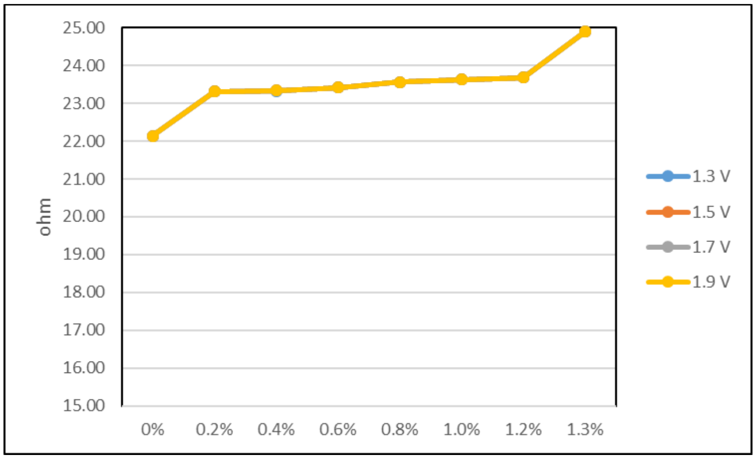


Figure A1-3 Resistance of Uninsulated Stainless Steel Yarn at Different Voltages and Tensile Strains

Table A1-4 Resistance of Uninsulated Stainless Steel Yarn at Different Frequencies and Tensile Strains

Unit: Ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	21.9964	22.1393	22.1436	22.1445	22.1442	22.1436
0.2%	23.0221	23.1420	23.1423	23.3186	23.3154	23.3140
0.4%	23.2338	23.3590	23.3492	23.3415	23.3391	23.3350
0.6%	23.2832	23.4172	23.4154	23.4187	23.4166	23.4201
0.8%	23.4270	23.5660	23.5601	23.5603	23.5620	23.5645
1.0%	23.4738	23.6001	23.5968	23.6333	23.6296	23.6263
1.2%	23.5597	23.6935	23.6916	23.6899	23.6858	23.6821
1.3%	24.7507	24.9006	24.9024	24.8977	24.8983	24.8979

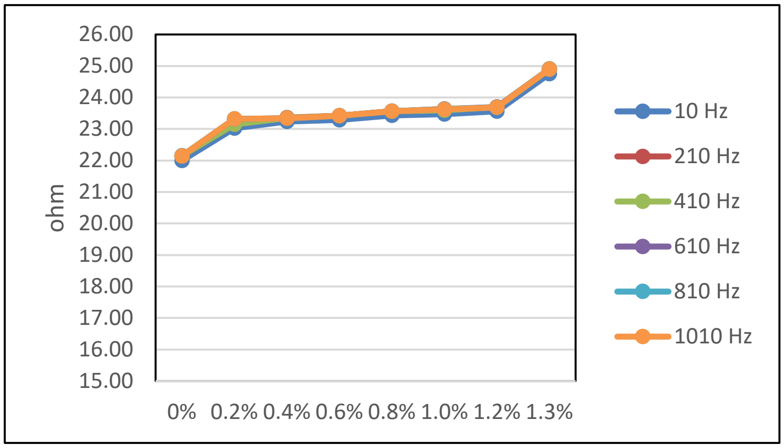


Figure A1-4 Resistance of Uninsulated Stainless Steel Yarn at Different Frequencies and Tensile Strains

1.2 Effect of Tensile Strain on Resistance of Copper wire

1.2.1 *Insulated* Copper Wire (Material B1)

There is no significant effect of tensile strain on the resistance of insulated copper wire when the strain is increased from 0% to breaking strain (9.8%) at different voltages as shown in Table A1-5 and Figure A1-5. Also, at any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated copper wires (Tables A1-5, A1-6 and Figures A1-5, A1-6).

Table A1-5. Resistance of Insulated Copper Wire at Different Voltages and Tensile Strains

Unit: Ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.2542	0.2556	0.2581	0.2594
0.2%	0.2560	0.2574	0.2599	0.2609
0.4%	0.2571	0.2585	0.2608	0.2618
0.6%	0.2569	0.2585	0.2607	0.2621
0.8%	0.2581	0.2600	0.2619	0.2652
1.0%	0.2581	0.2598	0.2617	0.2628
1.2%	0.2582	0.2599	0.2620	0.2632
3.0%	0.2613	0.2631	0.2651	0.2663
5.0%	0.2646	0.2670	0.2689	0.2698
8.0%	0.2700	0.2730	0.2745	0.2755
10.0%	0.2703	0.2729	0.2752	0.2756

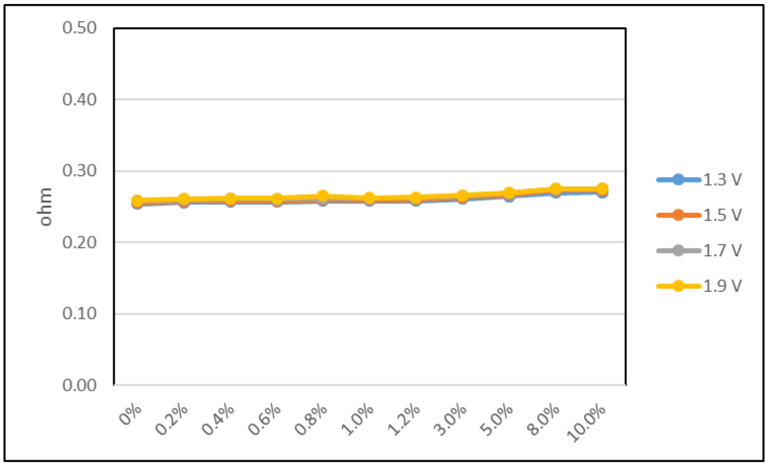


Figure A1-5 Resistance of Insulated Copper Wire at Different Voltages and Tensile Strains

Table A1-6 Resistance of Insulated Copper Wire at Different Frequencies and Tensile Strains

Unit: Ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.2568	0.2581	0.2585	0.2586	0.2594	0.2594
0.2%	0.2577	0.2596	0.2597	0.2599	0.2602	0.2609
0.4%	0.2596	0.2608	0.2614	0.2613	0.2616	0.2618
0.6%	0.2595	0.2608	0.2614	0.2616	0.2619	0.2621
0.8%	0.2655	0.2642	0.2647	0.2654	0.2680	0.2652
1.0%	0.2602	0.2618	0.2622	0.2626	0.2628	0.2628
1.2%	0.2603	0.2618	0.2622	0.2625	0.2628	0.2632
3.0%	0.2635	0.2650	0.2655	0.2657	0.2659	0.2663
5.0%	0.2678	0.2690	0.2694	0.2695	0.2698	0.2698
8.0%	0.2726	0.2742	0.2748	0.2751	0.2754	0.2755
10.0%	0.2730	0.2747	0.2754	0.2756	0.2757	0.2756

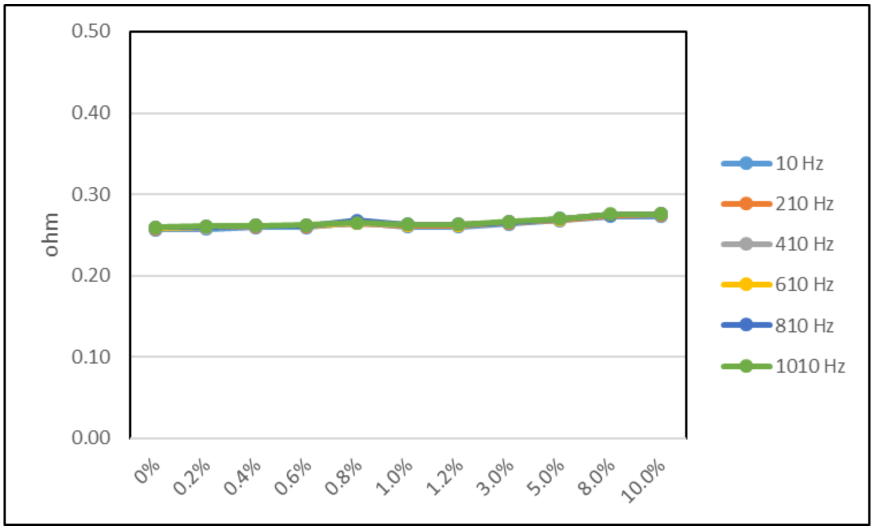


Figure A1-6 Resistance of Insulated Copper Wire at Different Frequencies and Tensile Strains

1.2.2 *Uninsulated* Copper Wire (Material B2)

There is no significant effect of tensile strain on the resistance of uninsulated copper wires when the strain is increased from 0% to breaking strain (29.93%) at different voltages as shown in Table A1-7 and Figure A1-7. Also, At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated copper wires (Tables A1-7, A1-8 and Figures A1-7, A1-8). Unlike the stainless steel yarn, which is a multifilament yarn, the copper wire is a single (solid) filament. Therefore, its response to tensile strain is different from that of the stainless steel yarn.

Table A1-7 Resistance of Uninsulated Copper Wire at Different Voltages and Tensile Strains

Unit: Ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.2603	0.2625	0.2653	0.2665
0.2%	0.2610	0.2631	0.2660	0.2675
0.4%	0.2626	0.2650	0.2673	0.2682
0.6%	0.2627	0.2651	0.2670	0.2684
0.8%	0.2629	0.2653	0.2675	0.2686
1.0%	0.2628	0.2651	0.2675	0.2686
1.2%	0.2630	0.2653	0.2673	0.2685
3.0%	0.2653	0.2681	0.2706	0.2715
5.0%	0.2696	0.2724	0.2745	0.2757
8.0%	0.2750	0.2788	0.2806	0.2815
10.0%	0.2798	0.2831	0.2848	0.2855
15.0%	0.2900	0.2932	0.2945	0.2951
20.0%	0.3010	0.3037	0.3049	0.3053
25.0%	0.3119	0.3143	0.3153	0.3154
30.0%	0.3238	0.3261	0.3267	0.3267

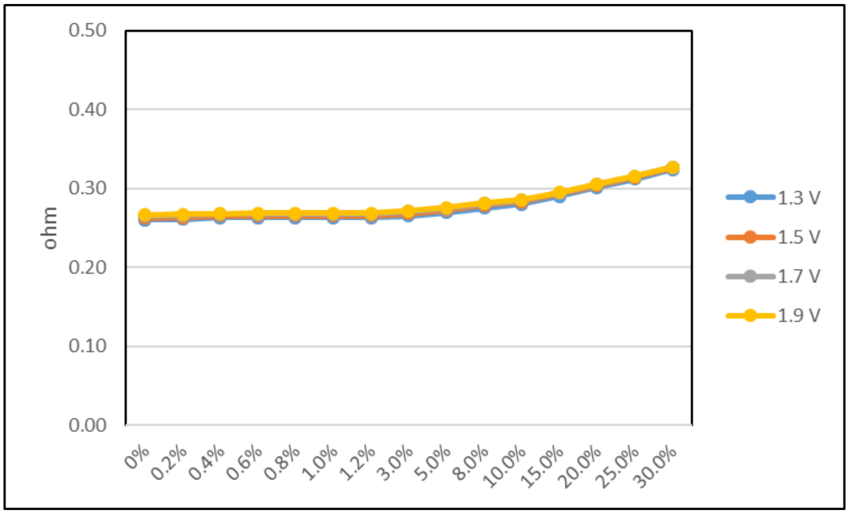


Figure A1-7 Resistance of Uninsulated Copper Wire at Different Voltages and Tensile Strains

Table A1-8 Resistance of Uninsulated Copper Wire at Different Frequencies and Tensile Strains

Unit: Ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.2616	0.2627	0.2630	0.2654	0.2661	0.2665
0.2%	0.2639	0.2657	0.2662	0.2663	0.2666	0.2675
0.4%	0.2654	0.2669	0.2673	0.2675	0.2678	0.2682
0.6%	0.2657	0.2673	0.2672	0.2675	0.2680	0.2684
0.8%	0.2658	0.2673	0.2677	0.2680	0.2682	0.2686
1.0%	0.2660	0.2673	0.2676	0.2679	0.2682	0.2686
1.2%	0.2660	0.2675	0.2678	0.2680	0.2685	0.2685
3.0%	0.2687	0.2705	0.2707	0.2711	0.2712	0.2715
5.0%	0.2729	0.2743	0.2748	0.2751	0.2753	0.2757
8.0%	0.2786	0.2804	0.2808	0.2813	0.2813	0.2815
10.0%	0.2827	0.2843	0.2847	0.2849	0.2852	0.2855
15.0%	0.2924	0.2941	0.2945	0.2946	0.2949	0.2951
20.0%	0.3026	0.3042	0.3045	0.3046	0.3049	0.3053
25.0%	0.3124	0.3143	0.3147	0.3150	0.3154	0.3154
30.0%	0.3237	0.3256	0.3260	0.3263	0.3266	0.3267

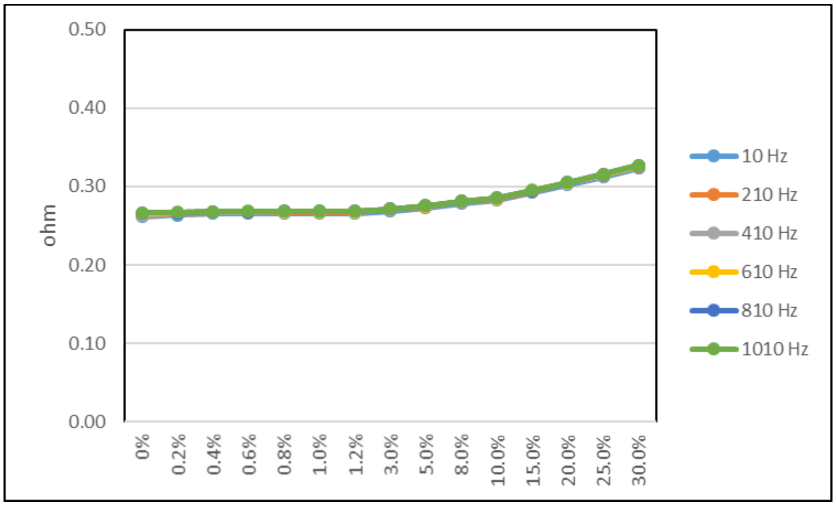


Figure A1-8 Resistance of Uninsulated Copper Wire at Different Frequencies and Tensile Strains

1.3 Effect of Tensile Strain on Resistance of Metal-Clad Aramid Yarn

1.3.1 *Insulated* Metal-Clad Aramid Yarn (Material C1)

There is no significant effect of tensile strain on the resistance of insulated metal-clad Aramid yarns when the strain is increased from 0% to breaking strain (2.16%) at different voltages as shown in Table A1-9 and Figure A1-9. Also, at any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated metal-clad Aramid yarns (Tables A1-9, A1-10 and Figures A1-9, A1-10).

Table A1-9 Resistance of Insulated Metal-Clad Aramid Yarn at Different Voltages and Tensile Strains

Unit: Ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.8423	0.8392	0.8372	0.8356
0.2%	0.8408	0.8378	0.8355	0.8339
0.4%	0.8404	0.8377	0.8356	0.8339
0.6%	0.8412	0.8383	0.8362	0.8346
0.8%	0.8427	0.8399	0.8376	0.8361
1.0%	0.8445	0.8417	0.8396	0.8379
1.2%	0.8469	0.8441	0.8419	0.8402

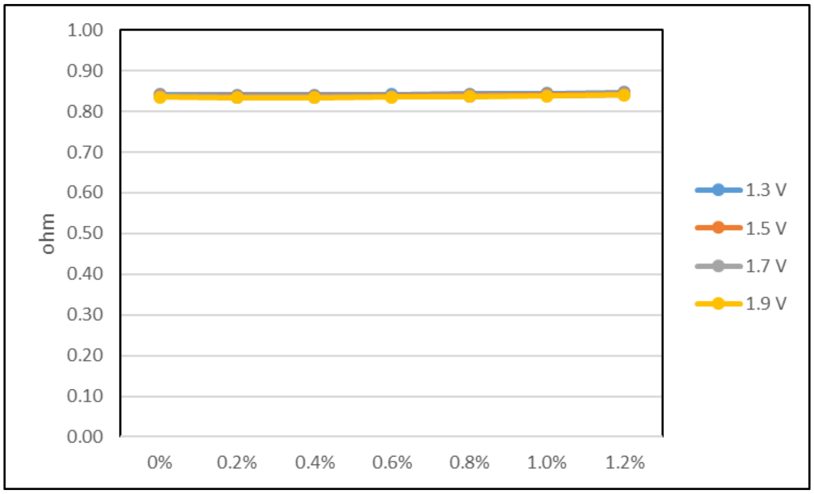


Figure A1-9 Resistance of Insulated Metal-Clad Aramid Yarn at Different Voltages and Tensile Strains

Table A1-10 Resistance of Insulated Metal-Clad Aramid Yarn at Different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.8310	0.8356	0.8349	0.8349	0.8351	0.8354
0.2%	0.8284	0.8339	0.8330	0.8331	0.8333	0.8337
0.4%	0.8285	0.8339	0.8332	0.8335	0.8336	0.8338
0.6%	0.8289	0.8346	0.8337	0.8337	0.8342	0.8345
0.8%	0.8308	0.8361	0.8354	0.8355	0.8357	0.8359
1.0%	0.8328	0.8379	0.8372	0.8374	0.8376	0.8378
1.2%	0.8351	0.8402	0.8396	0.8399	0.8400	0.8401

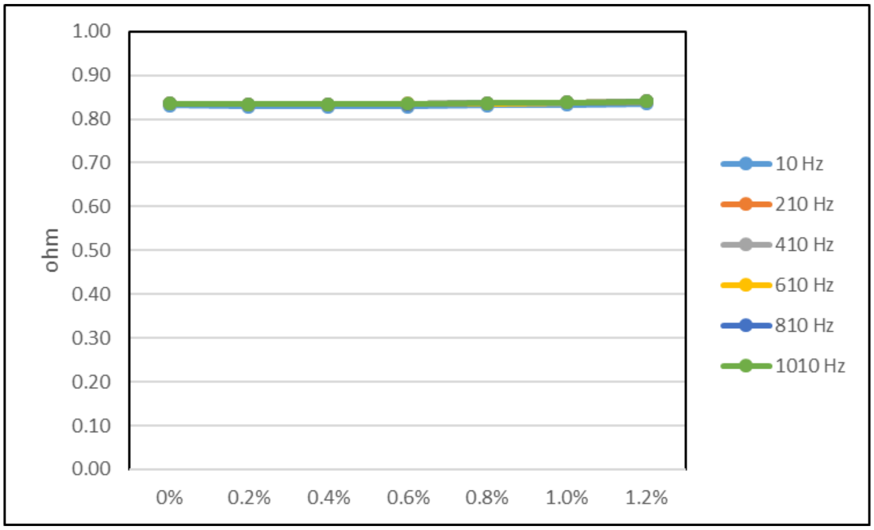


Figure A1-10 Resistance of Insulated Metal-Clad Aramid Yarn at Different Frequencies and Tensile Strains

1.3.2 *Uninsulated* Metal-Clad Aramid Yarn (Material C2)

The resistance of the uninsulated metal-clad Aramid yarn increases by 16% as the tensile strain increases from 0.2% to breaking strain (2.79%) at different voltages as shown in Table A1-11 and Figure A1-11. This behavior, i.e., change in resistance with tensile strain is in contrast to the insulated yarn and may be attributed to the difference in the modes of deformation of the two yarns. In the case of the uninsulated yarn, the fibrous strands in the yarn are probably retaining electrical connectivity – the result of a "non-catastrophic" failure of the yarn – while the insulated yarn is experiencing a catastrophic failure. The former causes "thinning" of the yarn leading to an increase in the resistance, while that phenomenon doesn't occur in the case of the insulated yarn. Thus, the behavior of the multifilament metal-clad Aramid yarn is similar to that of the multifilament stainless steel yarn. At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated metal-clad Aramid yarns (Tables A1-11, A1-12 and Figures A1-11, A1-12).

Table A1-11 Resistance of Uninsulated Metal-Clad Aramid Yarn at Different Voltages and Tensile Strains

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	1.2962	1.2957	1.2985	1.3004
0.2%	1.2201	1.2180	1.2203	1.2221
0.4%	1.2122	1.2097	1.2117	1.2137
0.6%	1.2144	1.2120	1.2141	1.2161
0.8%	1.2261	1.2239	1.2262	1.2282
1.0%	1.2481	1.2468	1.2491	1.2509
1.2%	1.2741	1.2731	1.2757	1.2775
2.0%	1.3803	1.3829	1.3854	1.3870
2.5%	1.4102	1.4136	1.4158	1.4172

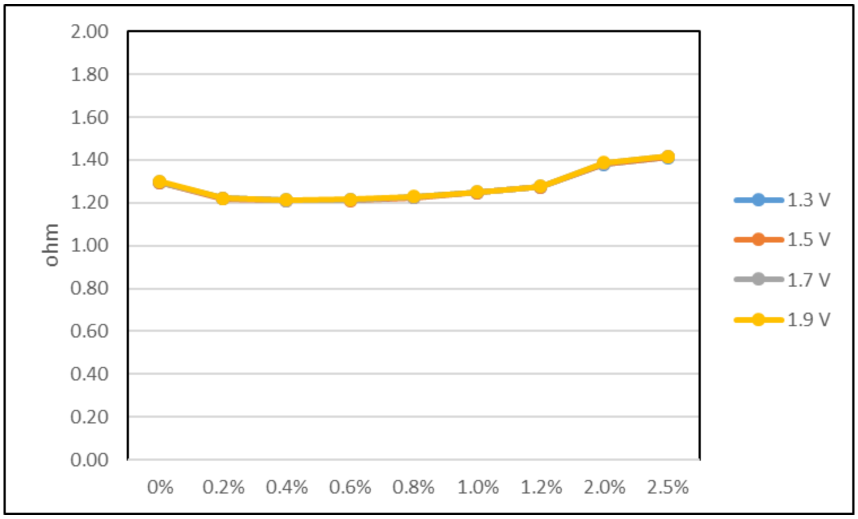


Figure A1-11 Resistance of Uninsulated Metal-Clad Aramid Yarn at Different Voltages and Tensile Strains

Table A1-12 Resistance of Uninsulated Metal-Clad Aramid Yarn at Different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	1.2935	1.3001	1.3002	1.3003	1.3003	1.3004
0.2%	1.2147	1.2218	1.2216	1.2218	1.2220	1.2221
0.4%	1.2067	1.2134	1.2134	1.2137	1.2137	1.2137
0.6%	1.2087	1.2153	1.2156	1.2157	1.2159	1.2161
0.8%	1.2209	1.2275	1.2278	1.2281	1.2285	1.2282
1.0%	1.2441	1.2507	1.2509	1.2509	1.2512	1.2509
1.2%	1.2698	1.2774	1.2772	1.2778	1.2781	1.2775
2.0%	1.3812	1.3878	1.3879	1.3872	1.3872	1.3870
2.5%	1.4101	1.4172	1.4171	1.4167	1.4172	1.4172

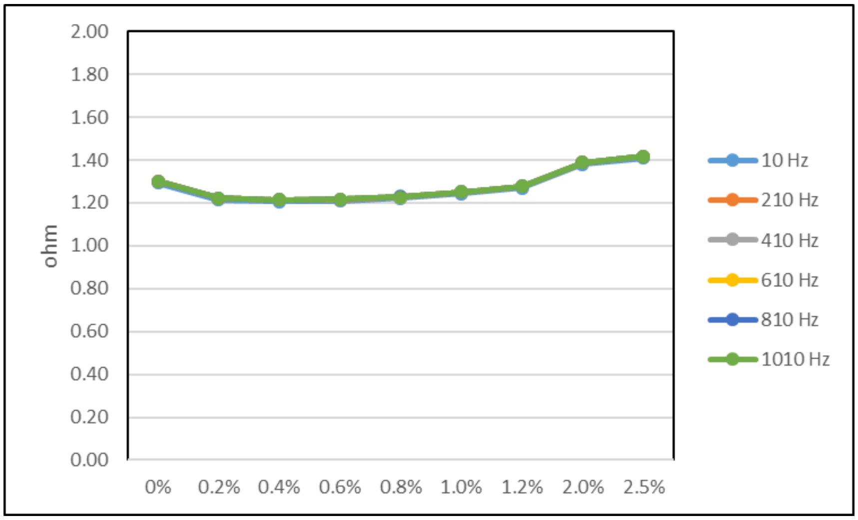


Figure A1-12 Resistance of Uninsulated Metal-Clad Aramid Yarn at Different Frequencies and Tensile Strains

1.4 Effect of Tensile Strain on Resistance of Nylon-Doped with Silver Yarn

1.4.1 *Insulated* Nylon-Doped with Silver Yarn (Material D1)

There is a significant effect of tensile strain on the resistance of insulated Nylon-doped with silver yarns when the strain is increased from 0% to breaking strain (19.13%) at different voltages. As shown in Table A1-13 and Figure A1-13, the resistance is approximately 88 Ohm in the range from 0% to 1.2% tensile strain; it then increases gradually to 587 Ohm at break – a significant increase of 560%. This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions). At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of insulated Nylon doped with silver yarns (Tables A1-13, A1-14 and Figures A1-13, A-14).

Table A1-13 Resistance of Insulated Nylon-Doped with Silver Yarn at Different Voltages and Tensile Strains

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	88.763	88.751	88.838	88.887
0.2%	88.595	88.550	88.538	88.594
0.4%	90.943	90.954	90.958	90.765
0.6%	89.720	89.699	89.717	89.711
0.8%	90.280	90.330	90.377	90.387
1.0%	93.110	93.210	93.331	93.409
1.2%	95.270	95.284	95.318	95.303
3.0%	119.504	119.531	119.450	119.483
5.0%	152.287	152.266	152.295	152.263
10.0%	239.830	239.839	239.769	239.849
15.0%	370.855	370.929	370.870	370.873
20.0%	586.547	586.679	586.477	586.465

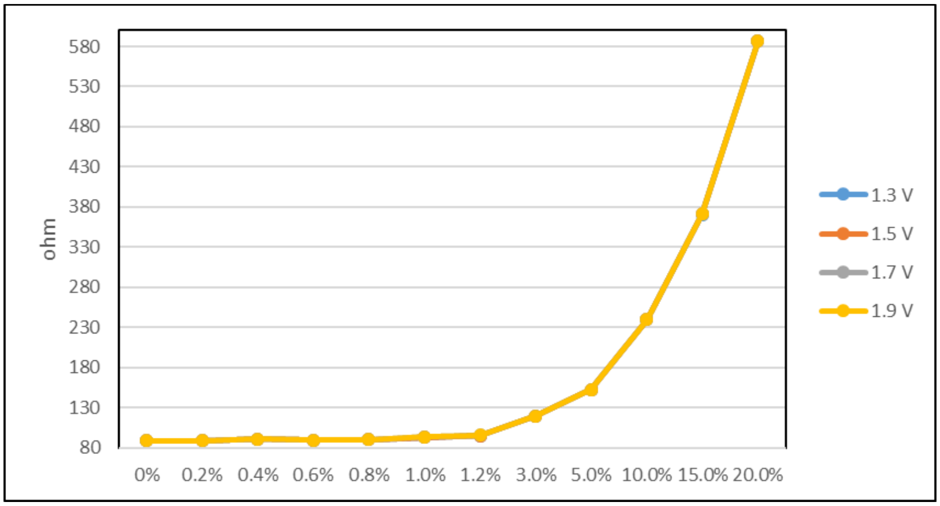


Figure A1-13 Resistance of Insulated Nylon-Doped with Silver Yarn at Different Voltages and Tensile Strains

Table A1-14 Resistance of Insulated Nylon-Doped with Silver Yarn at Different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	89.487	90.064	89.822	89.853	88.580	88.887
0.2%	89.344	89.500	89.565	89.681	89.653	88.594
0.4%	89.125	89.177	89.179	88.851	90.202	90.765
0.6%	90.169	90.052	89.651	89.814	89.734	89.711
0.8%	89.979	90.993	91.015	90.525	90.398	90.387
1.0%	91.099	92.097	92.528	93.227	92.872	93.409
1.2%	94.395	95.194	95.088	95.158	95.257	95.303
3.0%	118.445	119.249	119.425	119.365	119.422	119.483
5.0%	151.445	152.432	152.439	152.436	152.330	152.263
10.0%	239.161	240.972	240.670	240.222	240.022	239.849
15.0%	369.357	372.664	372.090	371.749	371.369	370.873
20.0%	586.190	593.396	590.599	589.288	587.463	586.465

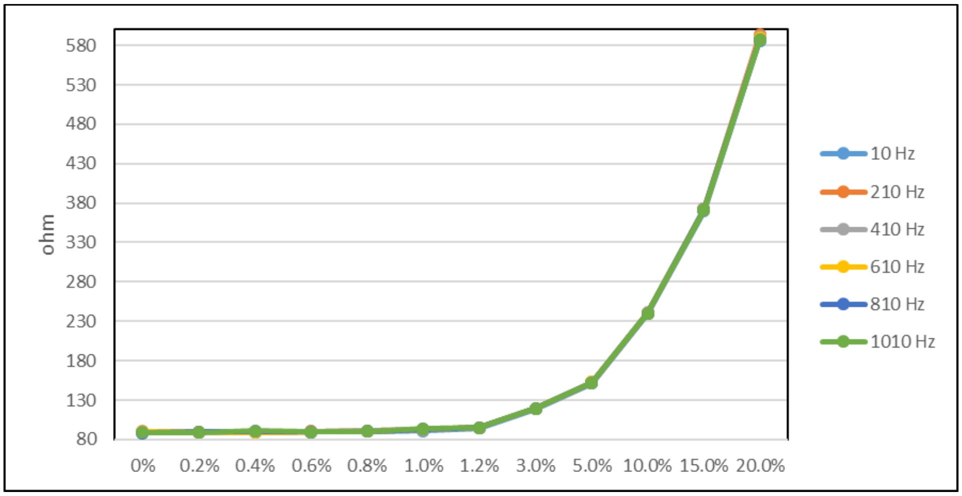


Figure A1-14 Resistance of Insulated Nylon-Doped with Silver Yarn at Different Frequencies and Tensile Strains

1.4.2 *Uninsulated* Nylon-Doped with Silver Yarn (Material D2)

There is a significant effect of tensile strain on the resistance of uninsulated Nylon-doped with silver yarns when the strain is increased from 0% to breaking strain (30.57%) at different voltages. The resistance changes from 61 Ohm at 0% strain to 67 Ohm at 1.2% tensile strain – an increase of 8%. It then increases gradually, but at a higher rate, to 983 Ohm at break – a remarkable increase of 1520% (Table A1-15 and Figure A1-15). This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions). The role of the insulation in "damping" the effect of the base yarn properties on the resistance of yarn is clear from the differences in the increases in the resistance for the two yarns, viz., 560% and 1520%, respectively. This means the uninsulated yarn was "less" constrained by the insulation – an important consideration when designing yarns for use as an information infrastructure component. At any given tensile strain, there is no significant effect of frequency and voltage on the resistance of uninsulated Nylon-doped with silver yarns (Tables A1-15, A1-16 and FiguresA1-15, A1-16).

Table A1-15 Resistance of Uninsulated Nylon-Doped with Silver Yarn at Different Voltages and Tensile Strains

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	60.711	60.732	60.690	60.661
0.2%	60.668	60.631	60.588	62.584
0.4%	59.963	61.154	61.096	63.404
0.6%	61.680	61.694	61.683	63.982
0.8%	62.952	62.963	62.942	64.628
1.0%	63.694	63.709	63.685	65.568
1.2%	64.632	64.642	64.612	66.704
3.0%	79.785	79.773	79.773	82.182
5.0%	93.808	93.817	93.813	97.079
10.0%	146.347	146.359	146.318	150.523
15.0%	237.314	237.337	237.326	242.725
20.0%	390.821	390.823	390.779	397.821
25.0%	632.844	632.866	632.766	646.020
30.0%	970.773	970.647	970.510	982.659

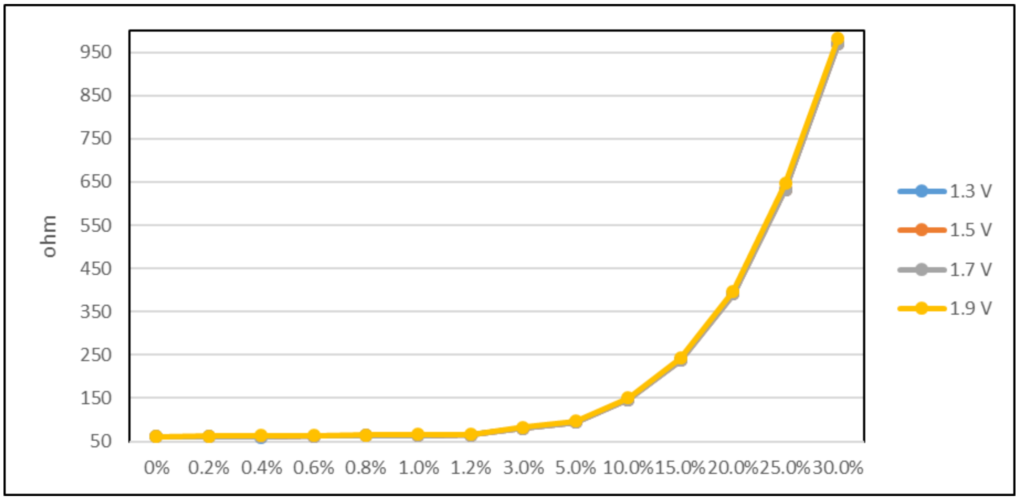


Figure A1-15 Resistance of Uninsulated Nylon-Doped with Silver Yarn at Different Voltages and Tensile Strains

Table A1-16 Resistance of Uninsulated Nylon-Doped with Silver Yarn at Different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	59.304	60.265	60.703	60.816	60.840	60.661
0.2%	59.946	59.914	59.732	59.788	59.705	62.584
0.4%	59.492	59.821	59.878	59.967	60.046	63.404
0.6%	60.351	60.599	60.566	60.577	60.581	63.982
0.8%	61.618	61.879	61.880	61.850	61.830	64.628
1.0%	62.276	62.546	62.536	62.540	62.546	65.568
1.2%	63.150	63.426	63.440	63.451	63.469	66.704
3.0%	78.123	78.427	78.397	78.332	78.309	82.182
5.0%	91.995	92.312	92.218	92.135	92.069	97.079
10.0%	143.495	143.970	143.711	143.459	143.276	150.523
15.0%	231.210	232.264	231.752	231.405	231.125	242.725
20.0%	377.519	379.633	378.839	378.162	377.607	397.821
25.0%	601.993	607.542	606.456	605.478	604.738	646.020
30.0%	879.834	887.901	885.181	882.983	881.206	982.659

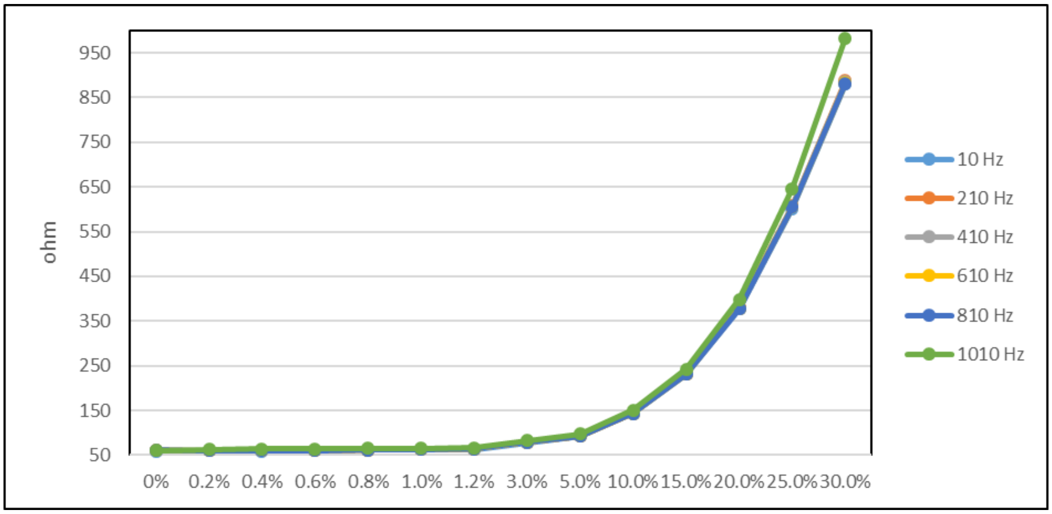


Figure A1-16 Resistance of Uninsulated Nylon-Doped with Silver Yarn at Different Frequencies and Tensile Strains

2. Electrical Properties of Fabrics with Woven-in Conductive Fibers

2.1 Effect of Tensile Strain on Resistance of Fabrics with Woven-in Stainless Steel Yarn

2.1.1 Fabric with Woven-in *Insulated* Stainless Steel Yarn (Material A1)

There is no significant effect of tensile strain on the resistance of insulated stainless steel yarn woven into the fabric when the strain is increased from 0% to 10% but the resistance increases by 33% at 12% tensile strain as shown in Table A1-17 and Figure A1-17. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of the insulated stainless steel yarn woven into the fabric (Tables A1-17, A1-18 and Figures A1-17, A1-18).

Table A1-17 Resistance of Insulated Stainless Steel Yarn in Woven Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	20.6572	20.6591	20.6557	20.6574
0.5%	20.6305	20.6329	20.6301	20.6324
1.0%	20.6167	20.6192	20.6164	20.6185
1.5%	20.6047	20.6080	20.6055	20.6081
3.0%	20.5943	20.5972	20.5949	20.5977
5.0%	20.5891	20.5922	20.5898	20.5925
10.0%	22.0377	22.0401	22.0351	22.0209
12.0%	27.5503	27.5262	27.5409	27.5623
15.0%	21.1754	21.1782	21.1757	21.1781
20.0%	130.9743	135.1585	129.7101	125.3560

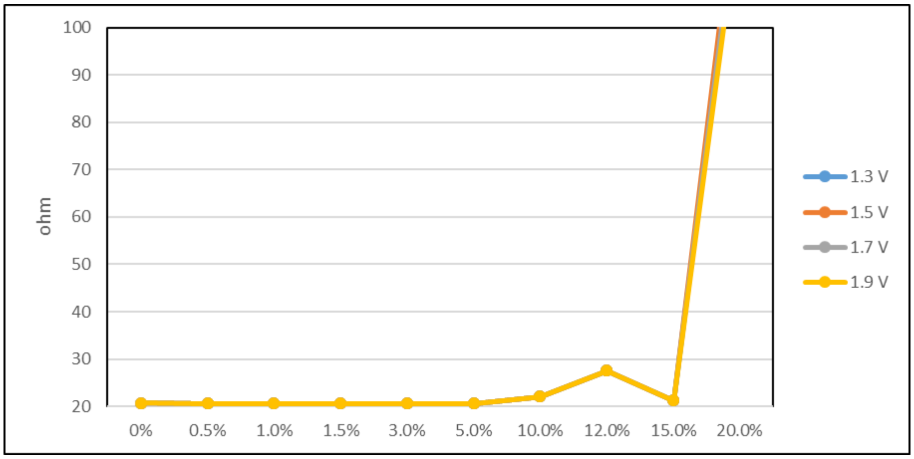


Figure A1-17 Resistance of Insulated Stainless Steel Yarn in Woven Fabric at different Tensile Strains and Voltages

Table A1-18 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Tensile Strains and Frequencies

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	20.6098	20.6927	20.6765	20.6677	20.6655	20.6574
0.5%	20.5227	20.6420	20.6408	20.6397	20.6362	20.6324
1.0%	20.5078	20.6264	20.6253	20.6244	20.6232	20.6185
1.5%	20.4917	20.6095	20.6098	20.6100	20.6085	20.6081
3.0%	20.4837	20.6007	20.6014	20.6000	20.5996	20.5977
5.0%	20.4751	20.5940	20.5952	20.5940	20.5937	20.5925
10.0%	21.8619	22.0034	21.9876	21.9825	22.0282	22.0209
12.0%	27.5627	27.5984	27.4005	27.5763	27.6671	27.5623
15.0%	21.0604	21.1824	21.1824	21.1829	21.1816	21.1781
20.0%	94.0668	108.1847	154.9348	122.9713	87.8674	125.3560

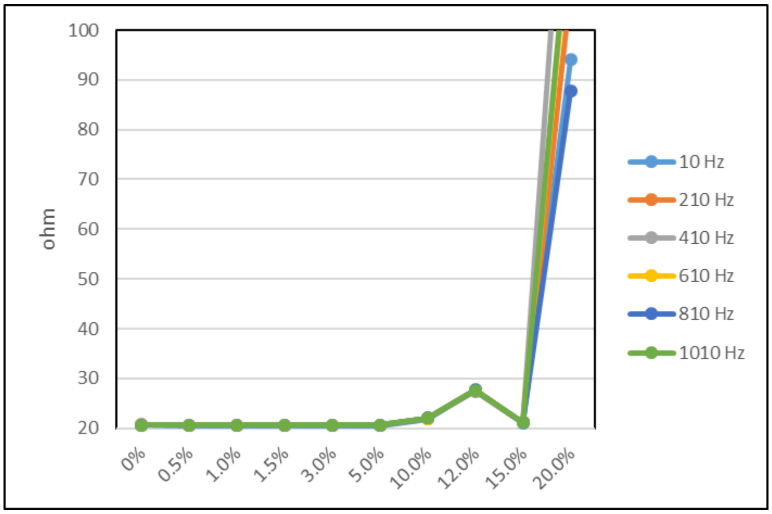


Figure A1-18 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strain

2.1.2 Fabric with Woven-in *Uninsulated* Stainless Steel Yarn (Material A2)

There is no significant effect of tensile strain on the resistance of uninsulated stainless steel yarn woven into a fabric when the strain increases from 0% to 10%. However, the resistance of this yarn increases by 33.87% at 15% strain as shown in Table A1-19 and Figure A1-19. This is because the yarn starts to break at around 10% strain although the breaking tensile strain of this material is 17.01%. At any given tensile strain, there is no significant effect of applied voltage and frequency on the resistance of an uninsulated stainless steel yarn woven into fabric (Tables A1-19, A1-20 & Figures A1-19, A1-20).

Table A1-19 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	20.5763	20.5746	20.5766	20.5661
0.5%	20.6832	20.6881	20.6852	20.6839
1.0%	20.7247	20.7288	20.7269	20.7304
1.5%	20.7435	20.7485	20.7490	20.7536
3.0%	20.6101	20.6166	20.6162	20.6204
5.0%	20.6063	20.6184	20.6208	20.6250
10.0%	20.9184	20.9214	20.9183	20.9192

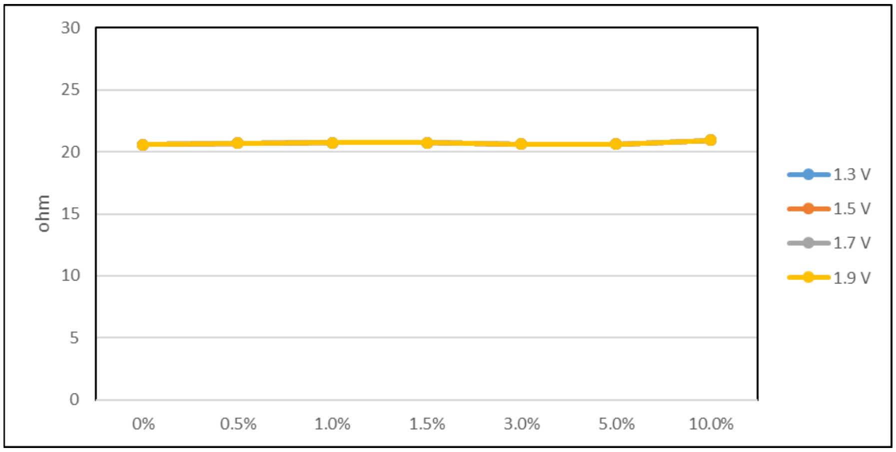


Figure A1-19 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-20 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	20.7368	20.7248	20.8108	20.7301	20.6919	20.5661
0.5%	20.4691	20.6555	20.7270	20.7002	20.6990	20.6839
1.0%	20.6199	20.7416	20.7429	20.7342	20.7332	20.7304
1.5%	20.6335	20.7549	20.7463	20.7466	20.7375	20.7536
3.0%	20.4784	20.5988	20.6088	20.6020	20.6093	20.6204
5.0%	20.4577	20.5928	20.5737	20.5797	20.5890	20.6250
10.0%	20.8939	20.9727	20.8734	20.9106	20.9289	20.9192

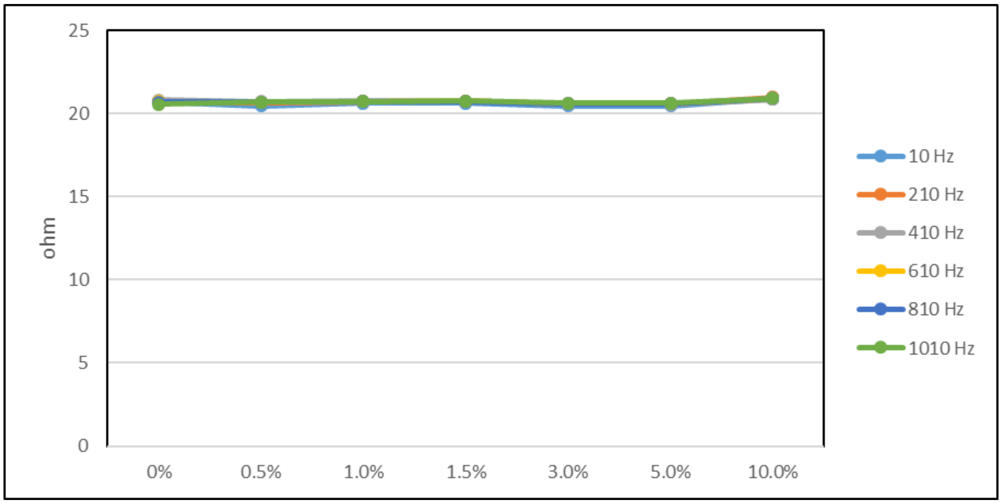


Figure A1-20 Resistance of Insulated Stainless Steel Yarn Woven into Fabric at different Frequencies and Tensile Strains

2.2 Effect of Tensile Strain on Resistance of Fabric with Woven-in Copper Wire

2.2.1 Fabric with Woven-in *Insulated* Copper Wire (Material B1)

There is no significant effect of tensile strain on the resistance of insulated copper wire woven in fabric when the strain is increased from 0% to 8% as shown in Table A1-21 and Figure A1-21. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of an insulated copper wire woven into fabric (Tables A1-21, A1-22 and Figures A1-21, A1-22).

Table A1-21 Resistance of Insulated Copper Wire Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.2236	0.2227	0.2238	0.2247
5.0%	0.2303	0.2298	0.2308	0.2318
8.0%	0.2280	0.2275	0.2280	0.2288

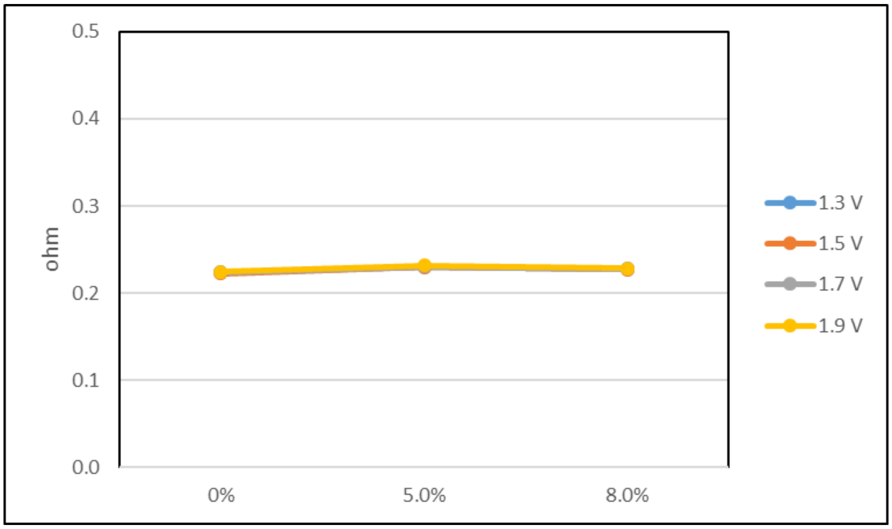


Figure A1-21 Resistance of Insulated Copper Wire Woven into Fabric at different Tensile Strains and Voltages

Table A1-22 Resistance of Insulated Copper Wire Woven into Fabric at different Tensile Strains and Frequencies

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.2353	0.2365	0.2240	0.2241	0.2243	0.2247
5.0%	0.2295	0.2307	0.2311	0.2313	0.2313	0.2318
8.0%	0.2269	0.2279	0.2284	0.2285	0.2286	0.2288

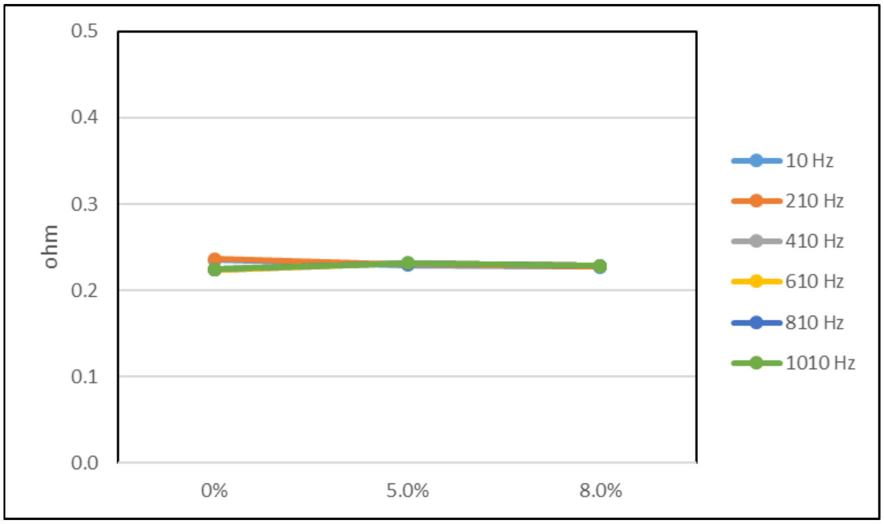


Figure A1-22 Resistance of Insulated Copper Wire Woven into Fabric at different Tensile Strains and Frequencies

2.2.2 Fabric with Woven-in *Uninsulated* Copper Wire (Material B2)

There is no significant effect of tensile strain on the resistance of uninsulated copper wire woven into fabric when the strain is increased from 0% to 20% (Table A1-23 and Figure A1-23). The average breaking tensile strain of this yarn is 24.9%. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of uninsulated copper yarn woven into fabric as shown in Tables A1-23, A1-24 and Figures A1-23, A1-24.

Table A1-23 Resistance of Uninsulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.2799	0.2815	0.2816	0.2837
5.0%	0.2862	0.2878	0.2885	0.2883
10.0%	0.2925	0.2947	0.2950	0.2952
15.0%	0.3030	0.3044	0.3049	0.3047

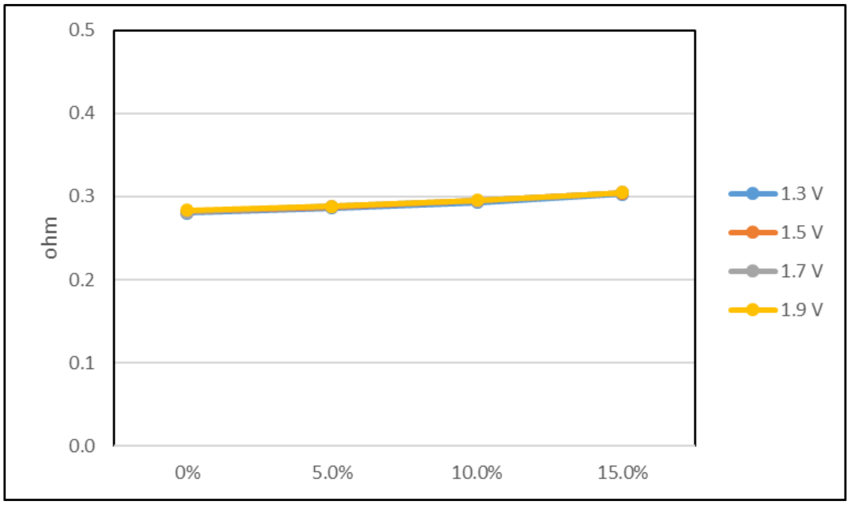


Figure A1-23 Resistance of Uninsulated Copper Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-24 Resistance of Uninsulated Copper Yarn Woven into Fabric at different Frequencies

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.2590	0.2592	0.2589	0.2645	0.2647	0.2837
5.0%	0.2869	0.2883	0.2887	0.2879	0.2881	0.2883
10.0%	0.2946	0.2958	0.2966	0.2920	0.2949	0.2952
15.0%	0.3020	0.3036	0.3041	0.3041	0.3043	0.3047

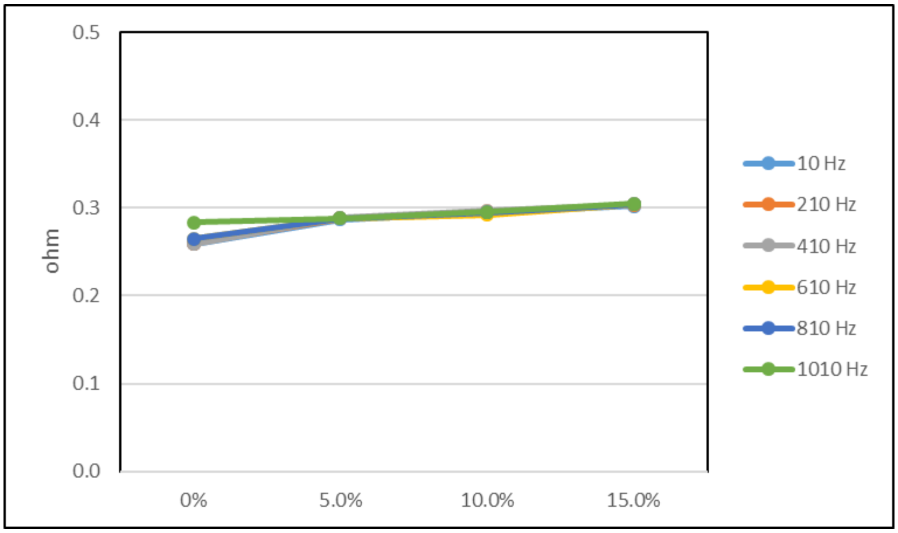


Figure A1-24 Resistance of Uninsulated Copper Yarn Woven into Fabric at different Frequencies and Tensile Strains

2.3 Effect of Tensile Strain on Resistance of Fabric with Woven-in Metal-Clad Aramid Yarn

2.3.1 Fabric with Woven-in *Insulated* Metal-Clad Aramid Yarn (Material C1)

There is no significant effect of tensile strain on the resistance of insulated Metal-Clad Aramid yarn woven into fabric when the strain is increased from 0% to 2% at different voltages. However, the resistance of the yarn starts to increase by 16.7% from 2% to 3% as shown in Table A1-25 and Figure A1-25. The breaking tensile strain of this yarn is 4.0%. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of insulated Metal-Clad Aramid yarn woven into fabric (Tables A1-25, A1-26 and Figures A1-25, A1-26).

Table A1-25 Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	0.7758	0.7725	0.7702	0.7683
1.0%	0.7749	0.7717	0.7692	0.7671
2.0%	0.7848	0.7817	0.7790	0.7770
3.0%	0.9120	0.9120	0.9054	0.9055

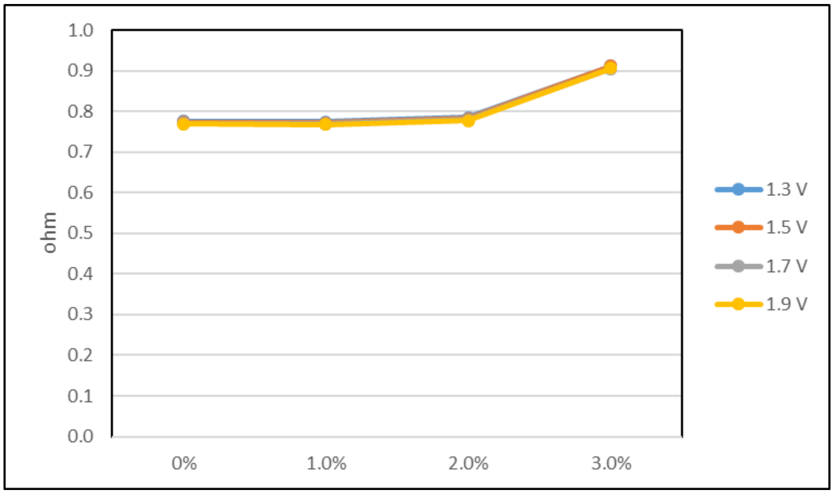


Figure A1-25 Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-25 Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	0.7643	0.7678	0.7681	0.7680	0.7683	0.7683
1.0%	0.7619	0.7658	0.7663	0.7665	0.7668	0.7671
2.0%	0.7721	0.7763	0.7765	0.7767	0.7768	0.7770
3.0%	0.8874	0.8998	0.9013	0.9150	0.9074	0.9055

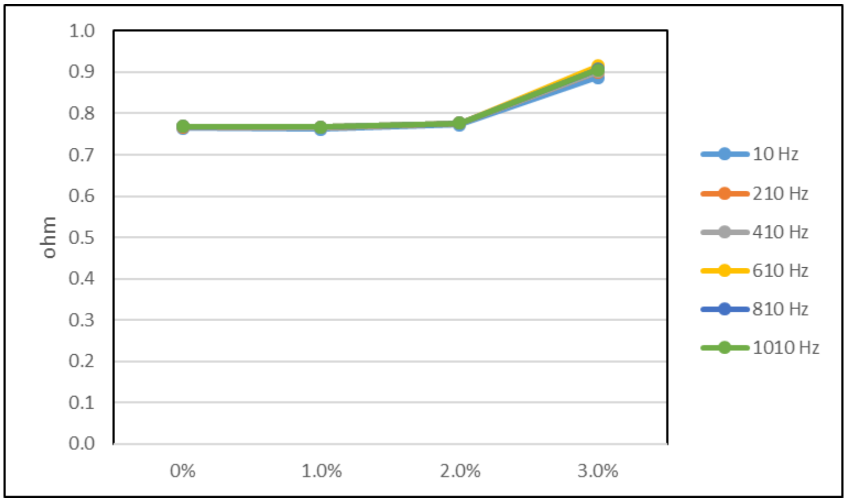


Figure A1-25 Resistance of Insulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

2.3.2 Fabric with Woven-in *Uninsulated* Metal-Clad Aramid Yarn (Material C2)

There is no significant effect of tensile strain on the resistance of uninsulated Metal-Clad Aramid yarn woven into fabric when the strain is increased from 0% to 5% at different voltages. The resistance of the yarn gradually increases by 7% when the tensile strain is increased from 5% to 10%, and by 5% when the strain increases from 10% to 15%. The overall increase in resistance of the yarn is 12.5% from 0% to 15% as shown in Table A1-26 and Figure A1-26. The breaking tensile strain of this yarn is 20%. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of uninsulated Metal-Clad Aramid yarn woven into fabric (Tables A1-26, A1-27 and Figure A1-26, A1-27).

Table A1-26 Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	1.2762	1.2748	1.2754	1.2767
2.0%	1.2784	1.2772	1.2779	1.2791
5.0%	1.2778	1.2766	1.2773	1.2787
10.0%	1.3714	1.3713	1.3722	1.3735
15.0%	1.4384	1.4396	1.4415	1.4423

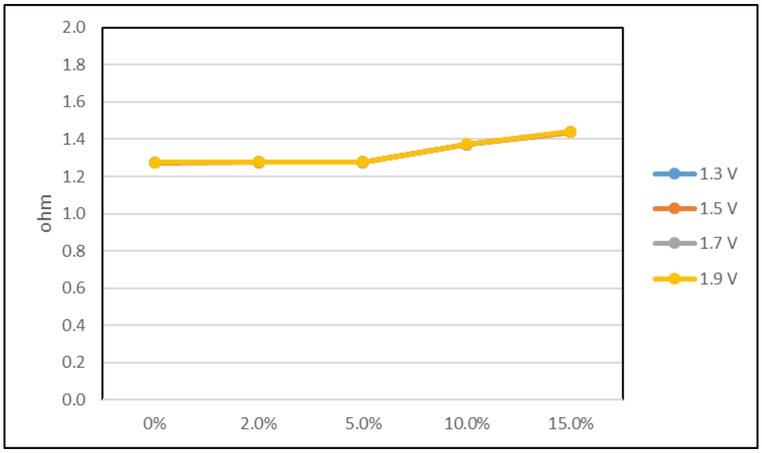


Figure A1-26 Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-27 Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	1.2717	1.2777	1.2775	1.2768	1.2770	1.2767
2.0%	1.2728	1.2794	1.2792	1.2793	1.2792	1.2791
5.0%	1.2726	1.2789	1.2790	1.2790	1.2787	1.2787
10.0%	1.3664	1.3721	1.3730	1.3727	1.3728	1.3735
15.0%	1.4356	1.4422	1.4407	1.4420	1.4418	1.4423

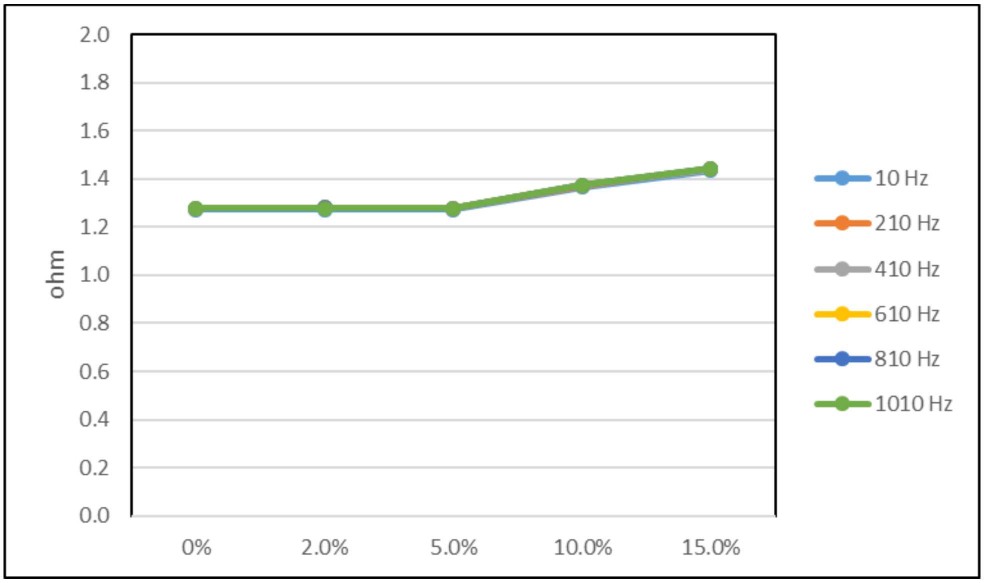


Figure A1-27 Resistance of Uninsulated Metal-Clad Aramid Yarn Woven into Fabric at different Frequencies and Tensile Strains

2.4 Effect of Tensile Strain on Resistance of Fabric with Woven-in Nylon-Doped with Silver Yarn

2.4.1 Fabric with Woven-in *Insulated* Nylon-Doped with Silver Yarn (Material D1)

There is a significant effect of tensile strain on the resistance of insulated Nylon doped with silver yarn woven into fabric when the strain increases from 0% to 25% at different voltages (breaking tensile strain is 29.8%). As shown in Table A1-28 and Figure A1-28, the resistance is approximately 88-89 ohm at 0% and 5% tensile strains. It then increases gradually to 470 Ohm at 25% – a significant increase of 435%. Unlike the case of other materials, this increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain, depending on processing conditions). At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of insulated Nylon doped with silver yarns woven into fabric (Tables A1-28, A1-29 and Figures A1-28, A1-29).

Table A1-28 Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	88.594	88.570	88.586	88.605
5.0%	89.185	89.166	89.184	89.200
10.0%	122.571	122.618	122.559	122.619
15.0%	201.996	202.009	202.022	202.001
20.0%	302.815	302.875	302.912	302.940
25.0%	467.806	467.949	467.772	468.009

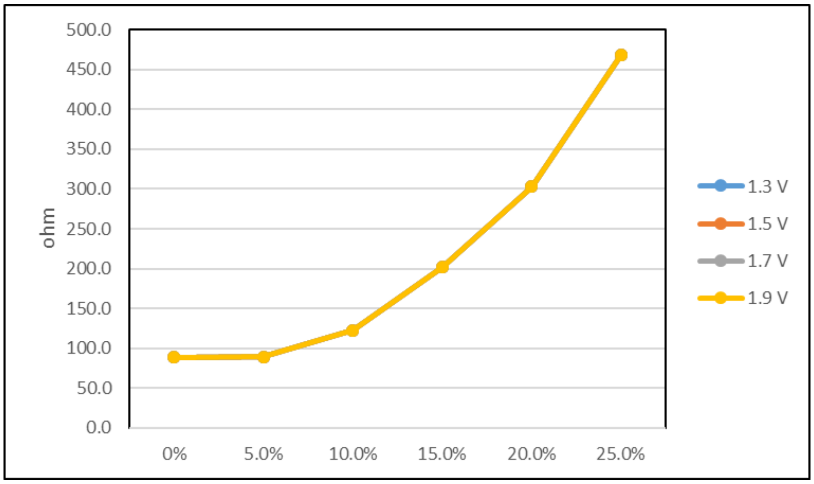


Figure A1-28 Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-29 Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	88.117	83.216	88.672	88.642	88.623	88.605
5.0%	88.620	89.237	89.228	89.215	89.210	89.200
10.0%	121.893	122.780	122.727	122.682	122.637	122.619
15.0%	201.487	202.843	202.587	202.344	202.156	202.001
20.0%	302.012	304.565	304.014	303.594	303.236	302.940
25.0%	465.773	470.793	469.771	469.006	468.608	468.009

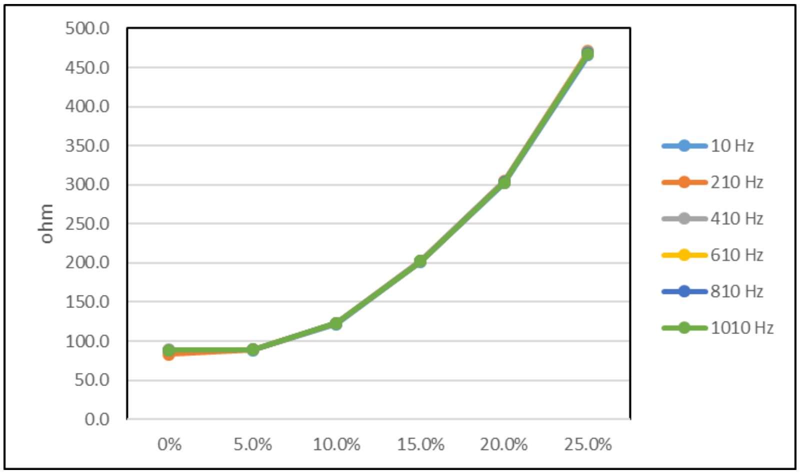


Figure A1-29 Resistance of Insulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

2.4.2 Fabric with Woven-in *Uninsulated* Nylon-Doped with Silver Yarn (Material D2)

There is no significant effect of tensile strain on the resistance of uninsulated Nylon doped with silver yarn woven into fabric when the tensile strain is increased from 0% to 10% at different voltages. The resistance starts to increase from 61 Ohm at 0% strain to 66 Ohm at 15% tensile strain – an increase of 8%. It then increases gradually, but at a higher rate, to 506 Ohm at 40% (breaking strain is 48.09%) – a remarkable increase of 730% (Table A1-30 and Figure A1-30). This increase can be attributed to the tensile properties of the base yarn, viz., Nylon, which is highly extensible (25%-30% breaking strain), depending on processing conditions. At any given tensile strain, there is no significant effect of voltage and frequency on the resistance of insulated Nylon doped with silver yarn woven into fabric (Tables A1-30, A1-31 and Figures A1-30, A1-31).

Table A1-30 Resistance of Uninsulated Nylon-Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Unit: ohm

	1.3 V	1.5 V	1.7 V	1.9 V
0%	60.934	60.965	60.961	60.961
5.0%	60.864	60.882	60.863	60.815
10.0%	61.737	61.762	61.749	61.729
15.0%	66.192	66.221	66.175	66.162
20.0%	92.140	92.105	92.170	92.234
25.0%	144.264	144.289	144.287	144.270
30.0%	212.989	212.957	212.948	212.887
35.0%	329.537	329.610	329.493	329.536
40.0%	506.320	506.608	505.965	506.008

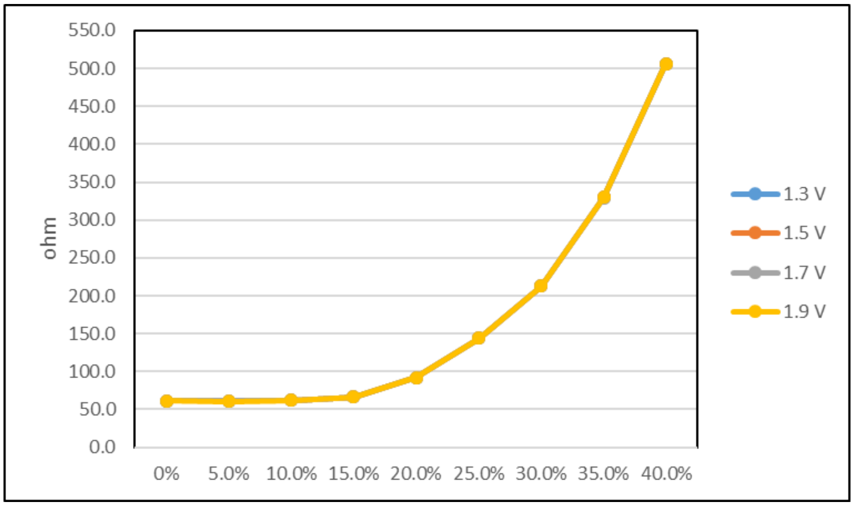


Figure A1-30 Resistance of Uninsulated Nylon-Doped with Silver Yarn Woven into Fabric at different Tensile Strains and Voltages

Table A1-31 Resistance of Uninsulated Nylon-Doped with Silver Yarn woven in fabric at different Frequencies and Tensile Strains

Unit: ohm

	10 Hz	210 Hz	410 Hz	610 Hz	810 Hz	1010 Hz
0%	60.343	60.802	60.799	60.860	60.855	60.961
5.0%	60.611	61.034	60.953	60.955	60.905	60.815
10.0%	61.330	61.765	61.714	61.722	61.737	61.729
15.0%	65.800	66.177	66.337	66.263	66.190	66.162
20.0%	92.162	92.611	92.681	92.320	92.072	92.234
25.0%	143.669	145.055	144.627	144.428	144.240	144.270
30.0%	212.542	214.113	213.728	213.322	212.985	212.887
35.0%	328.714	331.510	330.981	330.450	330.041	329.536
40.0%	503.217	508.883	507.298	507.063	506.575	506.008

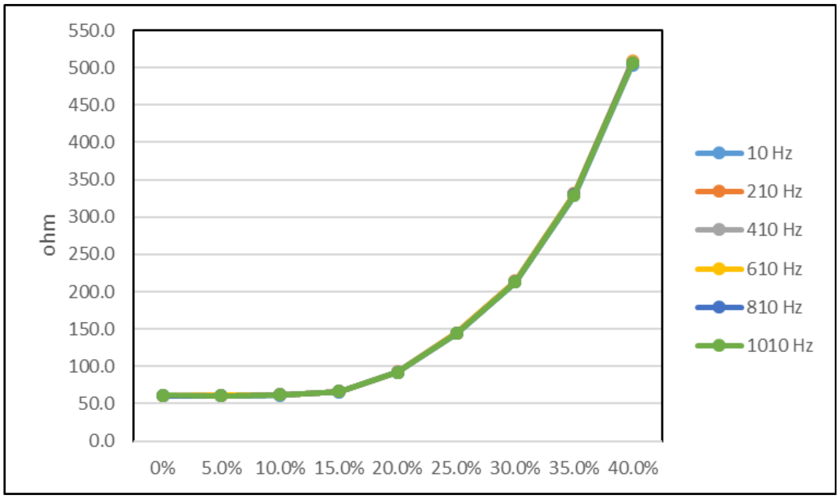


Figure A1-31 Resistance of Uninsulated Nylon Doped with Silver Yarn Woven into Fabric at different Frequencies and Tensile Strains

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