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The Wearable Motherboard™: The First Generation of Adaptive and Responsive Textile Structures (ARTS) for Medical Applications

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Abstract: Virtual reality (VR) has been making inroads into medicine in a broad spectrum of applications, including medical education, surgical training, telemedicine, surgery and the treatment of phobias and eating disorders. The extensive and innovative applications of VR in medicine, made possible by the rapid advancements in information technology, have been driven by the need to reduce the cost of healthcare while enhancing the quality of life for human beings.

In this paper, we discuss the design, development and realisation of an innovative technology known as the Georgia Tech Wearable Motherboard™ (GTWM), or the "Smart Shirt". The principal advantage of GTWM is that it provides, for the first time, a very systematic way of monitoring the vital signs of humans in an unobtrusive manner. The flexible data *bus* integrated into the structure transmits the information to monitoring devices such as an EKG machine, a temperature recorder, a voice recorder, etc. GTWM is lightweight and can be worn easily by anyone, from infants to senior citizens. We present the universal characteristics of the interface pioneered by the Georgia Tech Wearable Motherboard™ and explore the potential applications of the technology in areas ranging from combat to geriatric care. The GTWM is the realisation of a personal information processing system that gives new meaning to the term *ubiquitous* computing. Just as the spreadsheet pioneered the field of information processing that brought "computing to the masses", it is anticipated that the Georgia Tech Wearable Motherboard™ will bring personalised and affordable healthcare monitoring to the population at large.

Keywords: Healthcare; Intelligent clothing; Universal interface; Vital signs; Wearable information infrastructure; "Wearable Motherboard™"

Introduction

Virtual reality has paved the way for a new methodology that enhances the use of information in a broad spectrum of medical applications, including medical education, surgical training, telemedicine, surgery and the treatment of phobias and eating disorders. The extensive and innovative applications of VR in medicine have been made possible by the rapid advancements in information technology and human-computer interaction. For example, the abdominal simulator is an instructional tool that enables the surgeon to practice endoscopic surgical techniques [1]. It is also an important tool for teaching students the true anatomic relationships of intra-abdominal structures. The importance of VR in teaching and rehearsing difficult operations in neurosurgery has been discussed [2]. The role of VR in technical skills training for intravenous catheter placement has been explored [3]. The potential of VR to enhance the delivery of healthcare through telemedicine has been discussed [4]. Virtual Reality Therapy (VRT) has been used to overcome some of the difficulties inherent in the traditional treatment of phobias such as the fear of flying, fear of heights and fear of public speaking [5]. VRT can provide stimuli for patients who have difficulty in imagining scenes and/or are too phobic to experience real situations. VR has also been used for the treatment of eating disorders [6].

Thus, these examples of VR in medicine illustrate the importance of utilising advancements in innovative technology for the benefit of humankind. This approach of developing and harnessing technology to save lives and/or enhance the quality of life is especially critical in today's context of increasing healthcare costs.

The Twin Challenges of Healthcare and Battlefield Management

The cost of healthcare in the USA is escalating. In 1997, the US spent $1 trillion or 14% of its GNP on healthcare. According to a study conducted by William M. Mercer Inc., the price of healthcare costs climbed at the fastest rate in five years in 1998, with many business owners predicting even larger costs in the future [7]. The average cost of covering both active and retired employees rose to $4,164 per employee from $3,924 in 1997. Health benefit costs rose nearly twice as fast as the Consumer Price Index, which gained 3.4%. Furthermore, increasingly employees are bearing the burden of the higher costs of healthcare.

On the battlefield, the loss of even a single soldier in an engagement can potentially affect the nation's engagement strategy. This change in the psyche of the nation represents a significant paradigm shift from the past that, while saddened by the loss of its citizens, did not call for a change in its engagement policy. Therefore, any effort to minimise the loss of human life and/or enhance the quality of life has value that might be considered priceless.

Innovative technology holds the key to addressing the twin challenges of healthcare and battlefield management. According to Andy Grove, the Chairman of Intel Corp., the healthcare industry is facing an Internet-driven "strategic inflection point" or a time in which extreme change forever alters the competitive landscape of an industry, creating new opportunities and challenges [8].

We will now examine these twin challenges and the need for breakthrough technology in the form of a Wearable Motherboard™, or Smart Garment, to address them effectively.

The Healthcare Challenge: With universal access to information (e.g., through the Web), today's healthcare consumer is demanding more options and taking control in determining the course of healthcare. Therefore, the healthcare industry faces the following critical challenges that it must deal with:

- reduce healthcare costs while maintaining a high quality of care;
- provide access to care for as many people as possible;
- provide easy access to specialised professionals anywhere and anytime;
- shift the focus of healthcare expenditures from *treatment* to *prevention* through wellness programmes;
- control length of hospital stay and decentralise the provision of healthcare; and,
- address the increase in the aging population and caring for chronically ill patients.

The Battlefield Challenge: Unfortunately, casualties are associated with combat and sometimes are inevitable. Since medical resources are limited in a combat scenario, there is a critical need to make optimum use of the available resources to minimise damage from these combat injuries. In particular, if medical assistance can be provided to an injured soldier within the so-called "golden hour", mortality can be significantly reduced.

The Need for a Technology Solution

The healthcare industry must meet the challenge of balancing cost containment with maintenance of desired patient outcomes. Consequently, healthcare professionals are trying to provide patient care more efficiently and, whenever possible, in the least expensive setting, be that an intensive care unit (ICU), a hospital general care unit, a skilled nursing facility, or an outpatient clinic. Even a patient's home is becoming the site for many types of care or monitoring that once were provided only by hospitals. This has created a demand for portable, versatile medical devices that can be moved easily from the ICU all the way to a homecare setting.

There is a critical need for technologies that can potentially enhance the physician's abilities to address successfully even the most seemingly desperate of situations, whether it is the delivery of undernourished premature babies, or extending the life of a senior citizen through exploratory treatments and procedures. In other words, there is a need for an effective and mobile information infrastructure or monitoring system that can be tailored to the individual's requirements to take advantage of the advancements in telemedicine and information processing. If this information infrastructure can be realised in the form of a wearable garment that can collect, process, receive and transmit information about the wearer (e.g, body vital signs such as heart rate and temperature) to and from any remote location, it would address the twin challenges of healthcare and battlefield management. For example, patients in remote areas can have convenient access to healthcare specialists without having to travel, thereby minimising overall healthcare costs while enhancing the quality of care. In the future, the physical boundaries and distances that limit a specialist's healing area could disappear and patients could access any specialist they desire. In fact, taken one step further, potentially this approach could lead to a network of "speciality" centres around the world where each hospital could focus on a particular area of medicine rather than attempt to excel in all the specialties. Thus, as VR has clearly demonstrated in recent times, technological innovations have the potential to enhance the quality of life successfully while reducing healthcare costs.

In this paper, we discuss the design, development and realisation of one such innovative technology solution known as the Georgia Tech Wearable Motherboard™ or the Smart Shirt. We present the universal characteristics of the interface pioneered by the Wearable Motherboard™. We then explore the potential applications of the technology in areas ranging from combat care to geriatric care, and the realisation of a personal information processing system that gives new meaning to the term 'ubiquitous' computing.

Design and Development of the Wearable Motherboard™

In this section, we discuss the methodology for the design and development of the Georgia Tech Wearable Motherboard™ (GTWM).

Broad Performance Requirements

The US Department of Navy put out a "broad agency announcement" inviting white (concept) papers to create a system that was capable of alerting the medical triage unit (stationed near the battlefield) when a soldier was shot, along with some information on the soldier's condition characterising the extent of injury. As such, this announcement was very broad in the definition of the requirements and specified the following two key broad objectives of the Sensate Liner:

- to detect the penetration of a projectile (e.g. bullets and shrapnel); and
- to 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 developed by the US Defense Advanced Projects Research Agency (DARPA).

The Name "Wearable Motherboard™"

During the latter stages of the research, we coined the name "Wearable Motherboard™" to reflect the accomplishment of the research. Just as chips and other devices can be plugged into a computer motherboard, sensors and other information processing devices can be plugged into the Sensate Liners produced during the course of the research. Therefore, the name "Wearable Motherboard" is apt for the flexible, wearable and comfortable Sensate Liners. The name represents: (1) a natural evolution of the earlier names Sensate Liner and Woven Motherboard; and (2) the expansion of the initial scope and capability of a Sensate Liner targeted for combat casualty care to a much broader concept and spectrum of applications and capabilities.

Detailed Analysis of the Key Performance Requirements

The goals of the research project undertaken at Georgia Tech have been to conceptualise a system that would meet the two broad performance requirements, design the system applying the principles of concurrent engineering, produce the garment and demonstrate the realisation of the performance requirements.

The first step in this process was to identify clearly the various characteristics required by the customer (the US Navy) in the product being designed [9]. Therefore, using this information on the two key performance requirements, an extensive analysis was carried out. A detailed and more specific set of performance requirements was defined with the result shown in Fig. 1. These requirements are Functionality, Usability in Combat, Wearability, Durability, Manufacturability, Maintainability, Connectability and Affordability. The next step was to examine these requirements in-depth and to identify the key factors associated with each of them. These are also shown in Fig. 1. For example, Functionality implies that the GTWM must be able to detect the penetration of a projectile and should also monitor body vital signs – these are the two requirements identified in the broad agency announcement from the Navy.

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), minimising 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 Fig 1, Wearability implies that the GTWM should be lightweight, breathable, comfortable (form-fitting), easy to wear and take off, and provide easy access to wounds. These are critical requirements in combat conditions so that the soldier's performance is not hampered by the protective garment. The durability of the GTWM 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. Ease of manufacture is another key requirement since eventually the design (garment) should 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 GTWM is an important requirement for the hygiene of the soldiers in combat conditions; it should withstand field laundering, dry easily and be easily repairable (for minor damages). The developed GTWM should be easily connectable to sensors and the Personal Status Monitor (PSM) on the soldier. Finally, affordability of the proposed GTWM is another major requirement so that the garment can be made widely available to all combat soldiers to help ensure their personal survival, thereby directly contributing to the military mission as force enhancers.

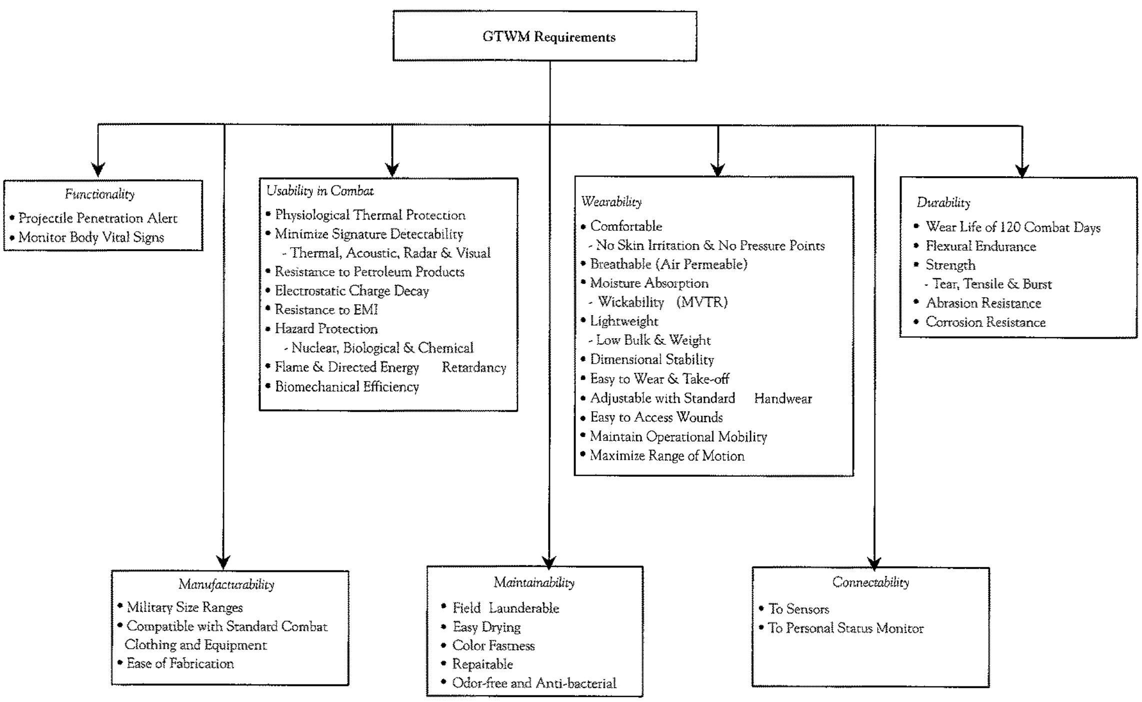

Fig. 1. GTWM: performance requirements.

Thus, in the first step of the conceptual design process, the broad performance requirements were translated into a larger set of clearly defined functions along with the associated factors (Fig. 1).

The GTWM 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 the literature, one was developed. Figure 2 shows the resulting overall GTWM Design and Development Framework and it encapsulates the modified QFD-type (Quality Function Deployment) methodology developed for achieving the project goals. The requirements are then translated into the appropriate properties of GTWM: sets of sensing and comfort properties. The properties lead to the specific design of the GTWM with a dual structure meeting the twin requirements of "sensing" and "comfort". These properties of the proposed design are achieved through the appropriate choice of materials and fabrication technologies by applying the corresponding design parameters as shown in Fig 2. These major facets in the proposed framework are linked together as shown by the arrows between the dotted boxes. The detailed analysis of the performance requirements, the methodology and the proposed design and development framework can be found in Rajamanickam et al. [10]. This generic framework can be easily modified to suit the specific end-use requirements associated with the garment. For instance, when creating GTWM for medical monitoring only, the requirement of "Usability in Combat" would not apply nor would the functionality of penetration detection.

This structured and analytical process eventually led to the design of the structure. The Wearable Motherboard™ consists of the following "building blocks" or modules that are totally integrated to create a garment (with intelligence) that feels and wears like any typical undershirt. The modules are:

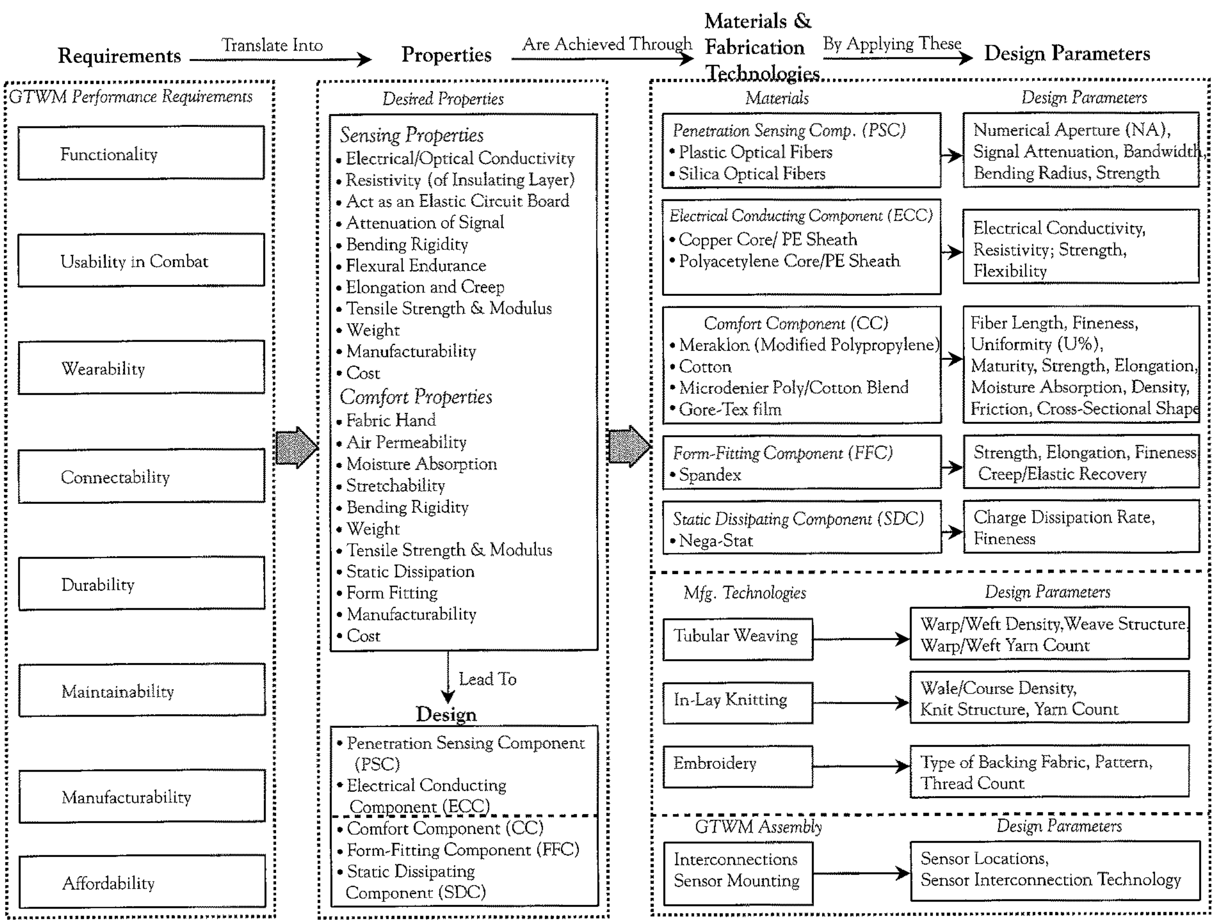

Fig. 2. GT wearable motherboard™: design and development framework.

- a *comfort component* to provide 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 from/to 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 minimise static build-up when the garment is worn.

The elegance of this design lies in the fact that these building blocks (like LEGO™ blocks) can be put together in *any* desired combination to produce structures to meet specific end-use requirements. For example, in creating a GTWM for healthcare applications (e.g. patient monitoring), the Penetration Sensing Component will not be included. The actual integration of the desired building blocks will occur during the production process through the inclusion of the appropriate fibres and yarns that provide the specific functionality associated with the building block. In and of itself, this design and development framework represents a significant contribution to systematising the process of designing structures and systems for a multitude of applications.

Production and Testing of GTWM

In this section, we discuss the production and testing of GTWM or the "Smart Shirt".

Production of GTWM

The schematic of one variation of the Wearable Motherboard™ is shown in Fig. 3. This design was woven into a single-piece garment (an undershirt) on a weaving machine to fit a 38–40 inch chest. The various "building blocks" integrated into the garment along with their relative positions in the garment are also shown in Fig. 3. Based on the in-depth analysis of the properties of the different fibres and materials, and their ability to meet the performance requirements, the following materials were chosen for the building blocks in the initial version of the Smart Shirt [10]:

- Meraklon (polypropylene fibre) for the comfort component;
- Plastic optical fibres for the penetration sensing component;
- Copper core with polyethylene sheath and doped nylon fibres with inorganic particles for the electrical conducting component;
- Spandex for the form-fitting component; and
- Nega-Stat™ for the static dissipating component.

The plastic optical fibre (POF) is spirally integrated into the structure during the fabric production process without any discontinuities at the armhole or the seams using a novel modification in the weaving process. With this innovative design, 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 fully-fashioned garment has been woven on a weaving machine.

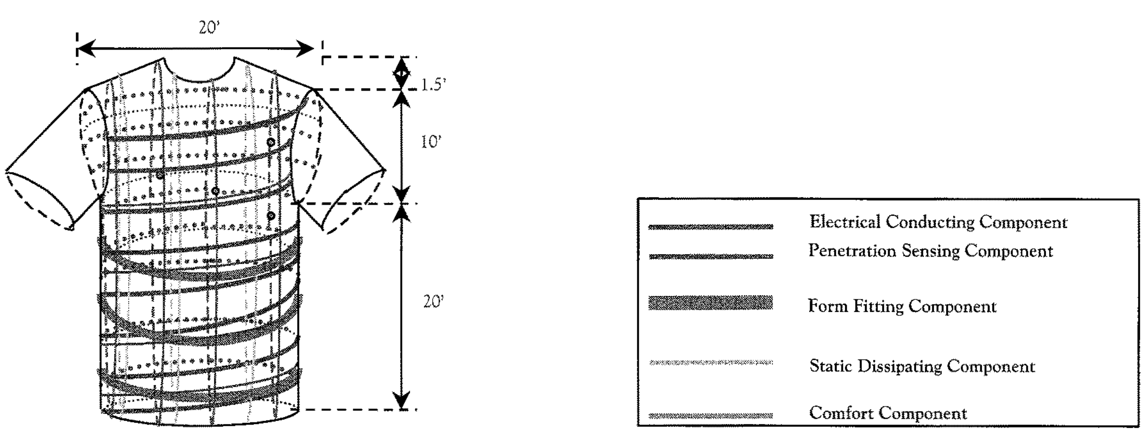

Fig. 3. Schematic of the Woven Wearable Motherboard™.

An interconnection technology was developed to transmit information to and from sensors mounted at any location on the body, thus creating a flexible "bus" structure. T-connectors – similar to "button clips" used in clothing – are attached to the yarns that serve as the data bus to carry the information from the sensors (e.g., EKG sensors) on the body. The sensors plug into these connectors and at the other end similar T-connectors are used to transmit the information to monitoring equipment or DARPA's personal status monitor. By making the sensors detachable from the garment, the versatility of GTWM has been significantly enhanced. Since human anthropometry is variable, sensors can be positioned on the right locations for all users without any constraints being imposed by GTWM. In essence, GTWM can be truly "customised". Moreover, it can be laundered without any damage to the sensors themselves. In addition to the fibre optic and speciality fibres that serve as sensors, and the data bus carrying sensory information from the wearer to the monitoring devices, sensors for monitoring the respiration rate (e.g., RespiTrace™ sensors) have been integrated into the structure, thus clearly demonstrating the capability to directly incorporate sensors into the garment.

Three generations of the Woven Wearable Motherboard™ have been produced and a knitted version of the Wearable Motherboard™ has also been created. Figure 4 shows the third generation Woven Wearable Motherboard™. The lighted optical fibres illustrate that GTWM is "armed" and ready to detect projectile penetration. The interconnection technology has been used to integrate sensors for monitoring the following vital signs: temperature, heart rate and respiration rate. In addition, a microphone has been attached to transmit the wearer's voice data to recording devices. Other sensors can be easily integrated into the structure. For instance, a sensor to detect oxygen levels or hazardous gases can be integrated into a variation of GTWM to be used by firefighters. This information, along with the vital signs, can be transmitted to the fire station where personnel can monitor the firefighter's condition continuously and provide appropriate instructions including ordering the individual to evacuate the scene, if necessary. Thus, this research has led to a truly and fully customisable "Wearable Motherboard™" or intelligent garment.

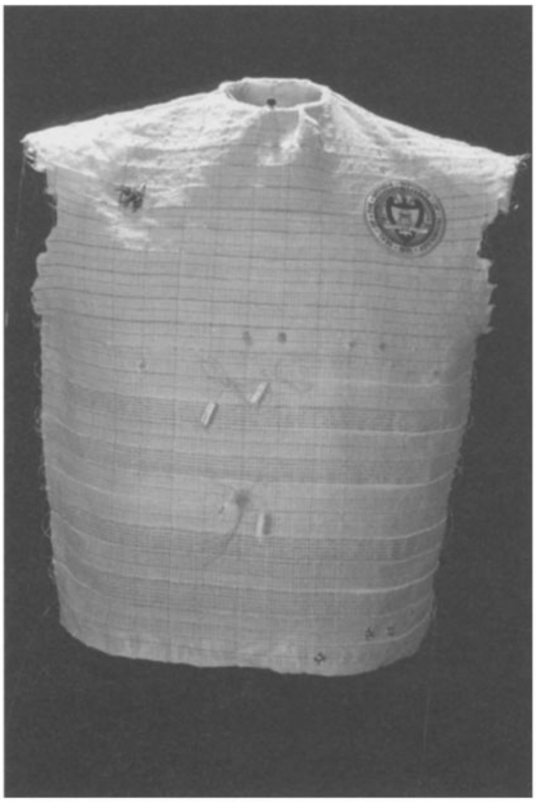

Fig. 4. Third generation woven GTWM.

Testing of GTWM

The penetration sensing and vital signs monitoring capabilities of GTWM were tested.

Penetration Sensing

The bench-top set-up for testing the penetration sensing capability is shown in Fig. 5. A low-power laser was used at one end of the plastic optical fibre (POF) to send pulses that "lit up" the structure, indicating that GTWM was armed and ready to detect any interruptions in the light flow that might be caused by a bullet or shrapnel penetrating the garment. At the other end of the POF, a photodiode connected to a power-measuring device measured the power output from the POF. The penetration of GTWM resulting in the breakage of POF was simulated by cutting the POF with a pair of scissors; when this happens, the power output at the other end on the measuring device falls to zero. The location of the actual penetration in the POF can be determined by an Optical Time Domain Reflectometer, an instrument used by telephone companies to pinpoint breaks in fibre optic cables.

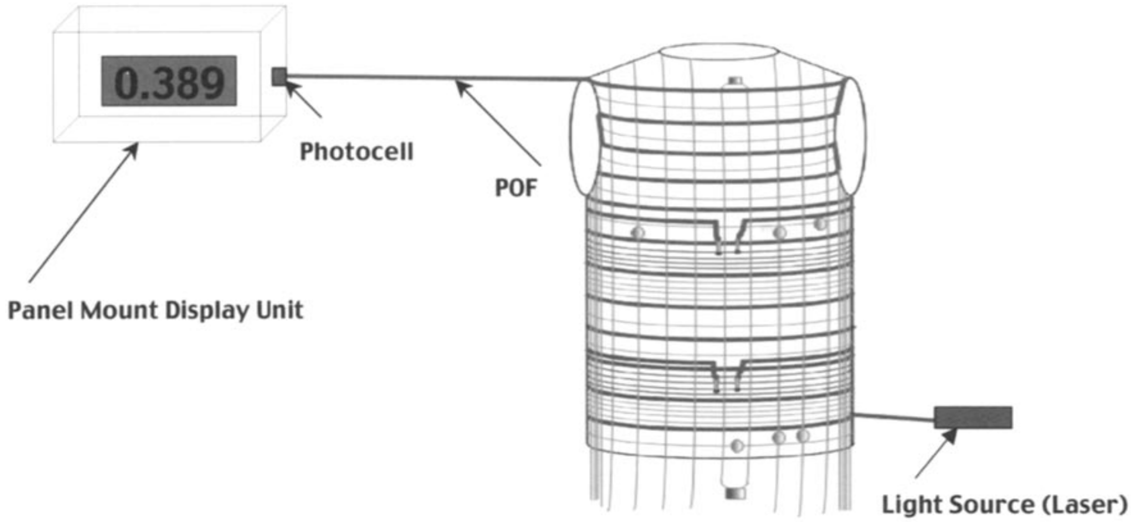

Fig. 5. Benchtop set-up for projectile penetration (POF).

Vital Signs Monitoring

Three EKG sensors, similar to the ones used in hospitals for EKG testing, were attached to the human subject, two on the left and one on the right side of the chest. The subject put on the GTWM just like any undershirt. The other side of the sensors on the body were "plugged" into the T-connectors on the GTWM worn by the subject. The three leads from the EKG monitor were connected to the T-connectors at the bottom of GTWM. Thus, the heart rate information collected by the three sensors on the body passed through the T-connectors at the top, through the GTWM and through the leads at the bottom of the GTWM and into the EKG monitor. Initial testing was done at Crawford Long Hospital followed by another more 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 Fig. 6. As seen from the figure, there is no difference between the control trace (using regular EKG sensors/setup) at the top and the trace

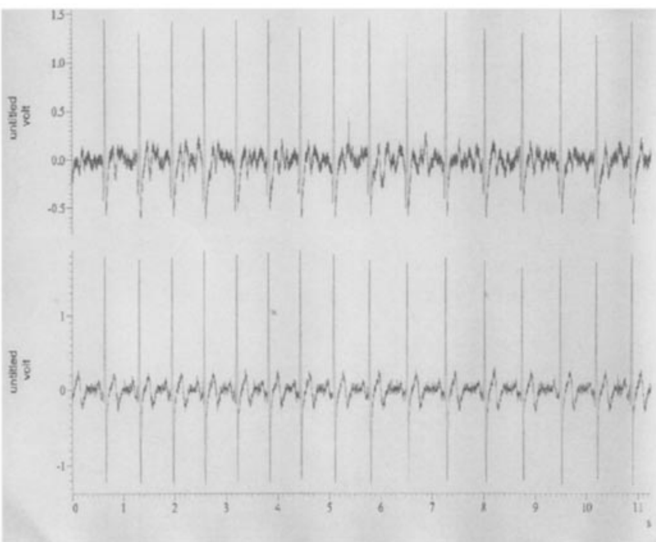

Fig. 6. EKG trace from the GTWM.

from the GTWM, thus conclusively demonstrating the vital sign monitoring capabilities of the GTWM.

In a combat situation, the vital signs and the penetration alert information will be transmitted from the GTWM into DARPA's Personal Status Monitor worn by the soldier for onward transmission to the medical triage unit. The soldier's vital signs can be continuously monitored by the triage unit and, if a penetration alert is received (when the soldier is shot), medical assistance can be provided immediately to the individual needing it the most, thus optimising the use of scarce medical resources in combat.

Voice Monitoring: To test the voice monitoring capabilities of GTWM, a microphone is plugged into the T-connectors on the GTWM worn by the subject. When the subject speaks, the voice is transmitted through the GTWM and is tapped at the T-connectors at the bottom of the garment and recorded in a computer. When the voice is played back, it is clear, thus demonstrating the voice monitoring capabilities of GTWM.

Comfort Testing: A participant wearing GTWM continuously for long periods of time evaluated the garment's comfort (Fig. 7). The participant's behaviour was observed to detect any discomfort and none was detected. The garment was also found to be easy to wear and take off since it is similar to a typical undershirt in terms of the weight, the form and fit, and the types of fibres in it.

For monitoring acutely ill patients who may not be able to wear the Smart Shirt over the head (like a typical undershirt), Velcro™ and zipper fasteners are used to attach the front and back of the Shirt creating a garment with full monitoring functionality (Figs 8 and 9).

Fig. 7. GTWM on a subject.

Fig. 8. Velcro attatchment on knitted Wearable Motherboard™.

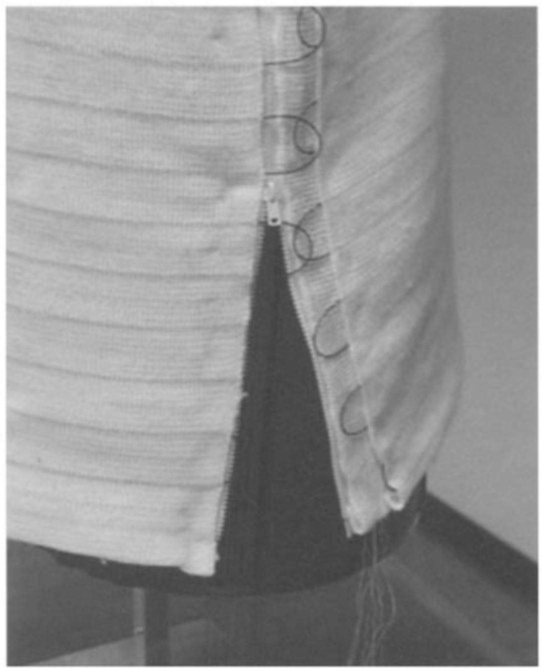

Fig. 9. Zipper attatchment on knitted Wearable Motherboard™.

Thus, a fully functional and comfortable Wearable Motherboard™ or Smart Shirt has been designed, developed and successfully tested for monitoring vital signs [11].

GTWM: Contributions and Potential Applications

This research on the design and development of GTWM has opened up new frontiers in fields such as personalised information processing, healthcare and telemedicine [12]. Applications of this technology could also be useful to monitor astronauts during space exploration. Until now, it has not been possible to create a personal information processor that was customisable, wearable and comfortable; neither has there been a garment that could be used for unobtrusive monitoring of humans on earth or in space for vital signs such as temperature, heart rate, etc. In this section, we discuss one of the significant contributions of the research and explore the key applications of GTWM in healthcare.

The Wearable Motherboard™ as a Universal Interface

Humans are used to wearing garments; they enjoy clothing and also know what to do with it; therefore, clothing as an interface is truly universal. Moreover, the user doesn't have to spend a lot of time and effort in learning how to use it. This universal interface of clothing can indeed be "tailored" to fit the user's physical needs and desires; at the same time, it must accommodate the constraints imposed by the ambient environment in which the user interacts with the interface, i.e., different climates, activities and occasions. 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 human-computer interfaces and is one that humans need, use and are very familiar with, that can be enjoyed and customised for every occasion. The Wearable Motherboard™ could become this universal interface and give new meaning to the term man–machine symbiosis'.

The benefits from a technology can be harnessed only if the technology is properly deployed. Proper deployment requires education and training in how to utilise the technology; moreover, the easier the interface, the greater the chances that the technology will be utilised. For instance, the standard "look and feel" of programs that run under the MS-Windows environment makes it easier for users to adopt and utilise the computing capability provided by the programs and the hardware. Just as the spreadsheet pioneered the field of information processing that brought "computing to the masses", it is possible that the Smart Shirt or GTWM with its universal interface will bring personalised and affordable healthcare monitoring to large segments of the population.

In his research on "wearable computers", Mann defined the following attributes for wearable computers: constant, unrestrictive to the user, unmonopolising of the user's attention, observable by the user, controllable by the user, attentive to the environment and personal [13]. Mann's criteria for wearable computers include it being eudaemonic, existential, and in constant operation and interaction [14].

The research on GTWM (carried out in parallel) focused on creating a personal wearable information interface that would be as comfortable as any other garment, rather than just making a computer wearable. However, a comparison with the attributes and criteria defined for wearable computers shows that GTWM meets these attributes and criteria and, indeed, may go beyond wearable computing.

Range of Potential Applications

The broad range of applications of GTWM in a variety of segments is summarised in Table 1. The table also shows the application type and the target population that can utilise the technology. A brief overview of the various applications follows:

Combat Casualty Care: GTWM can serve as a monitoring system for soldiers that is capable of alerting the medical triage unit (stationed near the battlefield) when a soldier is shot, along with information on the soldier's condition characterising the extent of injury and the soldier's vital signs. This was the original intent behind the research that led to the development of GTWM.

Healthcare and Telemedicine: The healthcare applications of GTWM are enormous and it greatly facilitates the practice of telemedicine, thus enhancing access to healthcare to patients in a variety of situations. These include patients recovering from

Table 1. The Wearable Motherboard™/Smart Shirt: potential applications

Segment	Application type	Target customer base
Military	Combat casualty care	Soldiers and support personnel in battlefield
Civilian	Medical monitoring	Patients: surgical recovery, psychiatric care
		Senior citizens: geriatric care, nursing homes
		Infants: SIDS prevention
		Teaching hospitals and medical research institutions
	Sports/performance monitoring	Athletes, individuals scuba diving, mountaineering, hiking
Space	Space experiments	Astronauts
Specialised	Mission critical/hazardous applications	Mining, mass transportation
Public safety	Fire fighting/law enforcement	Firefighters/police
Universal	Wearable mobile information infrastructure	All information processing applications

surgery at home (e.g., after heart surgery), geriatric patients (especially those in remote areas where the doctor/patient ratio is very small), potential applications for patients with psychiatric conditions (depression/anxiety), infants susceptible to SIDS (sudden infant death syndrome), and individuals prone to allergic reactions (e.g., anaphylaxis reaction from bee stings).

Sports and Athletics: GTWM can be used for the continuous monitoring of the vital signs of athletes to help them track and enhance their performance. In team sports, the coach can track the vital signs and the performance of the player on the field and make desired changes in the players on the field depending on the condition of the player.

Space Experiments: GTWM can be used for the monitoring of astronauts in space in an unobtrusive manner. The knowledge to be gained from medical experiments in space will lead to new discoveries and the advancement of the understanding of space.

Mission Critical/Hazardous Applications: Monitoring the vital signs of those engaged in mission critical or hazardous activities, such as pilots, miners, sailors, and nuclear engineers. Special-purpose sensors that can detect the presence of hazardous materials can be integrated into GTWM and enhance the occupational safety of the individuals.

Public Safety: Combining the Smart Shirt with a GPS (Global Positioning System) and monitoring the well-being of public safety officials (firefighters, police officers, etc.), their location and vital signs at all times, thereby increasing the safety and ability of these personnel to operate in remote and challenging conditions.

Personalised Information Processing: A revolutionary new way to customise information processing devices to "fit" the wearer by selecting and plugging in chips/sensors into the Wearable Motherboard™ (garment).

A detailed analysis of the characteristics of GTWM shows that it has the product appeal and features to meet the battlefield and healthcare challenges outlined in Section 1. These characteristics of GTWM are summarised in Table 2 and clearly demonstrate the realisation of a smart garment that can significantly transform healthcare in the next millennium.

Meeting the Healthcare Challenge

GTWM can contribute to reductions in healthcare costs while enhancing the quality of life. For instance, patients could wear GTWM at home and be monitored by a monitoring station (similar to home security monitoring companies), thereby avoiding hospital stay costs and reducing the overall cost of healthcare. At the same time, a home setting can contribute to faster recovery. As another example, when a baby version of GTWM is used for monitoring infants prone to SIDS, it can shift the focus from the treatment of infants who have suffered brain damage as a result of apnea to the prevention of the damage in the first place. Because GTWM can be tailored, it can be used across the entire population spectrum, from infants to senior citizens of both genders.

Product Versatility

The "plug and play" feature in GTWM greatly broadens its application areas. For instance, athletes can choose to have one set of sensors to monitor their performance on the field, while firefighters could have a different set of sensors (e.g., heart rate, temperature and hazardous gases) for their application. Thus, GTWM is a versatile platform and serves as a true motherboard™.

Product Appeal

GTWM is similar to any undershirt and it is comfortable, easy to wear and use. By separating the sensors from the garment, the maintenance of the garment has been enhanced. The current versions of the garment can be washed by hand. The initial tests have demonstrated the reliability of the system to monitor continuously the various vital signs. In terms of affordability, the anticipated costs to produce the Smart Shirt are in the $35 range (approximately £20.00). The costs associated with the required sensors and monitoring would vary depending on the individual application. Thus, conceptually, the Smart Shirt can be likened to a home alarm system. Just as the overall cost of the home monitoring system will depend on the number of points monitored, the types of sensors used and the desired response, the final cost of the Smart Shirt will also vary. This ability to customise greatly enhances the appeal of GTWM to a wide cross-section of the population.

We will now examine in depth a few of the GTWM application areas.

SIDS: The Problem and the GTWM Solution

Sudden Infant Death Syndrome (SIDS) is defined as the unexpected death of an infant under one year of age that is unexplained by history, post-mortem exam, and death scene investigation [15]. 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 7 out 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

Table 2. The Smart Shirt: meeting the healthcare and vital signs monitoring needs

Facet	Characteristic	The Smart Shirt/ Wearable Motherboard™
Meeting the healthcare challenge	Potential to reduce healthcare costs	Yes
	Facilitate shift from "treatment" to "prevention"	Yes
	Applicable across the healthcare continuum: ICU to homecare	Yes
	Enhance access to healthcare for population	Yes
	Usable by the population continuum: infants to senior citizens	Yes
Product capability	Monitor key vital signs	Yes (EKG, respiration rate, temperature)
	Integrated voice communication system	Yes
	Provision to monitor dangerous gases/materials	Yes
Product appeal	Affordable to consumers, healthcare professionals and institutions	Yes
	Comfortable and easy to use	Yes
	Reliable and maintainable	Yes
	Customisable, "plug and play" capability	Yes

victims, and infants who have experienced "Apparent Life-Threatening Episodes", i.e., turned blue and/ or stopped breathing [16]. In the United States, Georgia and the rest of the southeast are lagging behind the national trend in the decrease in deaths from SIDS because parents do not follow the proper guidelines when putting children to sleep [17].

Home apnea monitors are often prescribed for infants thought to be at high risk from SIDS [18]. At specialist apnea centers, such as the one at Emory Egleston Hospital, infants prone to SIDS are typically followed on home cardiorespiratory monitors that can record a child's heart rate (including the actual EKG waveform) and chest wall movements. The monitor constantly records and erases data about the child's heart rate and breathing. If certain preset parameters for apnea and/or bradycardia are violated, two functions are engaged. 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 can be downloaded via telephone modem to verify the events. In addition to saving lives by alerting the caregiver that an infant has stopped breathing or dropped his/her heart rate below what is considered a "safe" level, physicians may in certain instances be able to diagnose the cause for such events. Specialist physicians have diagnosed heart blocks, arrhythmias, and even seizures that were unsuspected by the primary care physician [19].

Key Problems with the Current Monitoring System

Currently, a major problem with home monitoring of infants is noncompliance. When asked why a family is reluctant to use the home monitor, two major causes have been identified. The first is due to the electrodes that are used to record the heart rate and respiratory effort. Currently, "rubberized" electrode patches are placed on the child's chest and held in place by applying a Velcro belt over the patches. If not applied properly, the belt and/or electrodes irritate the infant's skin (sometimes to the point of blistering and even bleeding); they can also trigger false alarms. Therefore, the parents may stop using the equipment. 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". Once again, the child continues to be unmonitored.

The Smart Solution

GTWM may provide the solution to the twin problems associated with noncompliance for two principal reasons. First, the sensors can be "plugged" into GTWM which is like any undershirt that can be customised to fit the child. Thus the discomfort from the existing Velcro belt can be minimised while ensuring the correct and easy placement of the sensors. Second, the wires that lead to the monitoring device can be plugged into the lower (hip/ waist) level of the GTWM and thereby minimise any risk of the infant getting choked by the wires.

Table 3 shows data from the US Census Bureau on the projected number of births over the next three decades. As monitoring technology improves (e.g., GTWM), the proportion of infants monitored in the hospital and at home will increase to minimise problems and fatalities. Thus, the potential of

Table 3. GTWM for infant care in United States, 2000–2030

Item	2000	2010	2020	2030
Projected number of births in United States (US Bureau of Census)	2,210,000	2,220,000	2,220,000	1,910,000
% of infants who would be monitored in hospital	10.00	50.00	75.00	80.00
% of infants who would need long-term monitoring for one year at home	0.50	1.00	2.00	2.00
Number of infants who would be monitored in hospital	221,000	1,110,000	1,665,000	1,528,000
Number of infants who would be monitored at home	11,050	22,200	44,400	38,200

GTWM in enhancing the quality of life for infants can be seen from the estimates given in the table.

Adult Healthcare and Telemedicine: The Problem and the GTWM Solution

With the decreasing number of doctors in rural areas, the doctor/patient ratio is, in certain instances, reaching unacceptable levels for ensuring a basic sense of comfort for people living in such areas. 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 there. This degree of uncertainty can greatly influence their post-operative recovery. Therefore, there is a need to monitor such patients at home continuously and give them peace of mind so that the positive psychological impact will speed up the recovery process.

The effectiveness of VR in providing mental care has been investigated [20]. Potentially, GTWM could be used in the regular monitoring of mentally ill patients (e.g., those suffering from manic depression) to gain a better understanding of the relationship between their vital signs and their behavioural patterns so that their treatments (e.g., medication) could be suitably modified. Other potential applications include the treatment of anxieties and phobias. 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.

The Smart Solution

GTWM provides the key to addressing adult healthcare needs in this broad range of scenarios. For instance, doctors can use it either continuously or intermittently to monitor remotely the desired vital signs of patients. Furthermore, persons who have known disorders can wear GTWM and their physical conditions can be under constant monitoring by medical personnel. For example, if the patient recovering at home from heart surgery is wearing the Smart Shirt, the EKG can be transmitted regularly either wirelessly or through computer modems to the hospital. This monitoring will help the patient feel more "secure" and will facilitate the recuperation while simultaneously reducing the cost and time associated with recovery. Moreover, in the event of an emergency, the doctor can be notified instantaneously leading to prompt and effective treatment.

For example, Table 4 shows data from the US Census Bureau on the projected number of individuals who will be 65 years or older over the next three decades – a sizable segment of the total US population. The number of elderly individuals that is expected to require monitoring is also shown in the table; the impact of GTWM on enhancing geriatric care by providing an unobtrusive monitoring system is significant for both the elderly and the caregivers who might not necessarily live in the same household.

Hazardous and Mission-Critical Applications: The Problem and the GTWM Solution

According to the US National Sleep Federation (NSF), industrial accidents and lowered productivity – combined with car, truck, and plane crashes – cost the American economy up to $100 billion a year [21]. In a survey of 1000 adults conducted in 1998 by NSF, 62% admitted to driving when they were drowsy and 27% to dozing off at the wheel. The conservative estimate of cost of car crashes due to fatigue alone runs to $12.5 billion a year.

Table 4. GTWM for geriatric care

Item	2000	2010	2020	2030
Projected population older than 65 (US Bureau of Census)	34,700,000	39,400,000	53,200,000	69,400,000
Elderly population requiring monitoring (%)	0.10	0.30	0.60	1.20
Number of elderly patients requiring continuous monitoring	34,700	118,200	319,200	832,800

With the society's desire for instantaneous response and service, from pizza delivery to stock trading, companies are demanding more of their employees which could lead to fatigue and accidents. Therefore, it might be desirable to have a system that could monitor the individual's physical responses and prevent fatigue-related accidents.

The Smart Solution

GTWM has the potential to address this need for unobtrusively monitoring individuals engaged in hazardous and mission-critical applications. For instance, a pilot's vital signs could be monitored by GTWM and recorded in the aircraft's black box. In the event of a plane crash, it would be easier to determine if the crash occurred because the pilot was incapacitated (e.g. due to a massive heart attack). Sleep studies have focused on the use of EEG or electroencephalogram [22]. GTWM may serve as a potential research tool in such sleep studies and also in determining if there is a relationship between fatigue (reflected in body vital signs) and falling sleep at the wheel. If such a relationship does indeed exist, GTWM can serve at the core of a system to anticipate and avoid fatigue-related accidents.

Space Experiments: The Problem and the GTWM Solution

In recent years, NASA has conducted several space experiments to study the effects of microgravity on the human body in order to enhance the ability of humans to perform future space missions – including building the Space Station and other planned programmes in the human exploration of space. During the Shuttle mission (STS-95) in November 1998, Senator John Glenn participated as a 77-year-old payload specialist to carry out studies on the commonalties between the effects of space flight and aging [23]. The series of experiments was aimed at studying the effect of microgravity on vital signs during sleep. During the mission, Glenn went to bed wearing sensors that detected everything from brain waves to body motion. Airflow sensors were used for monitoring apnea. A younger astronaut, Chiaki Mukai from Japan, also participated in the experiments. The process of donning the sensors and making the connections was cumbersome. The set-up time for each experiment was nearly an hour with the participation of 1–2 astronauts onboard the Shuttle [24]. Assuming (in round figures) that a typical Shuttle launch costs $375 million, on this nine-day mission with seven astronauts on board, the cost/astronaut-hour in space comes to $248,016. With four experiments conducted during the mission, the total cost incurred by NASA to set up the four experiments comes to eight astronaut-hours, or $1,984,127.

The Smart Solution

Using GTWM to prepare the astronaut for the facet of the experiment that monitored vital signs would have been akin to wearing an undershirt. The Senator could have done it by himself and without any assistance from fellow astronauts. Assuming that it would take approximately 15 minutes (a very generous time allowance) to put on the Smart Shirt and make the necessary connections to the monitoring equipment, the set-up time for the four experiments would be about an hour of the Senator's time at a cost of $248,016. However, it is important to note that this estimated cost refers only to the part of the experiment dealing with the monitoring of the vital signs. Regardless of the potential cost savings from the use of GTWM, the garment would have been unobtrusive and, with its "plug and play" capability, different sets of sensors could have been plugged in during the different experiments.

Adaptive and Responsive Textile Structures (ARTS): The GTWM Solution

Adaptive and Responsive Textile Structures (ARTS) are the new class of textile garments pioneered by GTWM that can sense the vital signs of the individual wearing the garment, analyse the data using built-in intelligence and provide a suitable response based on the analysis. For example, some individuals are susceptible to *anaphylaxis* reaction (an allergic reaction) when stung by a bee or after taking certain medications and need a shot of epinephrine (adrenaline) immediately to prevent serious illness or even a fatality. Future research on GTWM could lead to the development and incorporation of (i) appropriate sensors on GTWM to detect the anaphylaxis reaction; (ii) adaptive mechanisms that can monitor the wearer's vital signs and create a response; and (iii) a built-in "feedback" mechanism that can effect the "responsive" action (administer an injection). Thus, GTWM represents yet another significant milestone in the endeavour to save and enhance the quality of human life.

In short, with its universal interface of a garment, GTWM has the potential to be used in a wide variety of healthcare applications in the daily life of individuals ranging from infants to senior citizens.

Conclusions

GTWM is an effective and mobile information infrastructure that can be tailored to the individual's requirements to take advantage of the advancements in telemedicine and information processing. Just as special purpose chips and processors can be plugged into a computer motherboard™ to obtain the required information processing capability, GTWM is the intelligent garment or information infrastructure into which the wearer can "plug in" the desired sensors and devices. In short, the "Wearable Motherboard™" fulfills the twin roles of being: (1) a flexible information infrastructure that will facilitate the paradigm of ubiquitous computing; and (2) a system for monitoring the vital signs of individuals in an efficient and cost-effective manner with a "universal" interface of clothing.

Moreover, GTWM has the potential to revolutionise a wide range of human endeavours and significantly enhance the quality of life. The widespread utilisation of the technology can not only enhance the quality and accessibility of healthcare but also decrease its cost. At the same time, the potential for the new paradigm of wearable, flexible information processing systems is waiting to be explored and GTWM represents a significant contribution in that direction.

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