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Recent developments and trends in biomedical sensors

Mehmet Engin [a,*], Alparslan Demirel [b], Erkan Zeki Engin [a], Musa Fedakar [c]

[a] *Engineering Faculty, Department of Electrical and Electronics Engineering, Bornova, 35100 İzmir, Turkey*
[b] *Ege University, Engineering Faculty, Department of Textile Engineering, Bornova, 35100 İzmir, Turkey*
[c] *Ege University, Engineering Faculty, Department of Bioengineering, Bornova, 35100 İzmir, Turkey*

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Abstract

The aim of this paper is to give brief information on recent developments and trends in biomedical sensors. We also tried to reveal the close correlation between biomedical sensors and smart (intelligent) textiles. We emphasized on the concept of wearable, as we have considered this notion the transition zone between the contemporary biomedical sensors and smart (intelligent) textiles.

Keywords: Biomedical technology; Smart textile; Sensors; Biomedical signal acquisition

1. Introduction

Biomedical sensors have a vital importance in modern life. We live in an epoch of computerization for every field of life. As we all know, computers can only process the data. Data must be collected, stored if necessary, and transferred to a computer. Biomedical sensors are designed for collecting data. It might be necessary to collect data for inpatients in hospital environment, in home for homebound patients, or for outpatients. This is an equivalent of monitoring. Monitoring is a necessary activity in risky environments such as mining, diving, mountain climbing, and especially in all sorts of military and security actions. All of these broad application fields have common requirements. The biomedical sensor should be compact and should not force the wearer to leave the comfort zone. These common requirements suggest the smart (intelligent) textiles along with the notion of wearable.

The concept of a wearable corresponds for a device that is always attached to a person (i.e. that can constantly be carried, unlike a personal stereo), is comfortable and easy to keep and use,

* Corresponding author. Tel./fax: +90 232 388 60 24.
E-mail address: mengin@bornova.ege.edu.tr (M. Engin).

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and is "as unobtrusive as clothing". Wearable systems are quite non-obtrusive devices that allow physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months. They typically rely on wireless, miniature sensors enclosed in patches or bandages, or in items that can be worn, such as a ring or a shirt. Recent advances in miniature devices, as well as mobile computing, have fostered a dramatic growth of interest for wearable technology. Wearable sensors and systems have evolved to the point that they can be considered ready for clinical application. This is due not only to the tremendous increase in research efforts devoted to this area in the past few years but also to the large number of companies that have recently started investing aggressively in the development of wearable products for clinical applications. Stable trends showing a growth in the use of this technology suggest that soon wearable systems will be part of routine clinical evaluations. The interest for wearable systems originates from the need for monitoring patients over extensive periods. The usual clinical or hospital monitoring of physiologic events such as the electrocardiogram or blood pressure provides only a brief window on the physiology of the patient. There are at least three major limitations that can be mentioned for clinical monitoring: (1) They are likely to fail in sampling rare events that may be of profound diagnostic, prognostic, or therapeutic importance, (2) they fail to measure physiologic responses during normal periods of activity, rest, and sleep, which are more realistic indicators of the health of the patient and the patient response to therapeutic intervention (even clinically based efforts to simulate physiologic stressors, such as exercise testing, may fail to replicate the true physiologic response to the complex array of physical and psycho logic stressors that confront the patient), and (3) brief periods of monitoring cannot capture the circadian variation in physiologic signals that appear to reflect the progression of disease. Wearable devices that can intermittently or continuously monitor and record relevant physiologic signals therefore offer an important solution to the limits imposed by traditional monitoring schemes [1,2].

1.1. User requirements for wearable sensors

When more and more sensors and measurement devices are integrated in the daily living environment of the ordinary users, certain implementation issues become essential: *Reliability*, *robustness*, *and durability*; The environments in which the sensors need to operate vary, and the users are non-specialists, not necessarily aware of the technical limits of usage (despite the fact that they may be described in the user's manual). Hence, the sensors should provide reliable results under a wide range of operation conditions, they should be robust against external disturbances (physical, electrical, electromagnetical, etc.), and they should not get easily broken down, even if the instructions for usage are violated.

Appearance/unobtrusiveness: The sensors are integrated into the everyday life of the users. Hence, they should either fit by their look to the individual's preferences, or they should "disappear"; i.e., be as unobtrusive as possible. Which option is more preferable depends on the application: while in the wellness management application a trendy wrist-worn heart-rate monitor may be appreciated as a kind of a status symbol, but in the case of independent living a wrist-worn alarm device that looks too much like a technical aid may be regarded as a stigmatizing element for an elderly person.

User identification: While especially wearable devices are often personal and hence their results may be associated with a specific user, this is not true in all cases. For example, a single heart-rate monitor might be used by many persons. This requires some method for identification of the user in order to associate the measurement data with a right person.

Communication: The sensors and measurement devices should be capable of transferring their measurement results to some central data storage preferably fully automatically, or at least so easily, that it does not pose a burden to the user. The appropriate level of ease depends on the application, but the simple added value principle should be followed; i.e., the value experienced by the user should exceed the effort needed to use the system.

Zero maintenance and fault recovery: As more and more sensors and devices are embedded in our environment, ease of maintenance becomes essential. An important issue in the case of health monitoring is self-calibration; i.e., finding ways to guarantee that the sensor performance does not deteriorate over time. An issue is the battery life of the sensors and measurement devices a user should not need to worry about constantly changing or recharging batteries for the multitude of sensors and devices at home. Finally, if something in the system goes wrong, there should be automated methods for assuring a proper fault recovery of the system without complex re-installations and other procedures [3].

1.2. Wearable sensors materials

Until now, and this is unlikely to change soon most integrated circuits are made with silicon, due to its unrivalled semiconductor properties. Silicon is not perfect though. An important drawback, in the meantime, for wearable electronics, is the fact that silicon is not flexible. This makes it difficult for large silicon chips to form part of clothing as they are rigid and may cause discomfort. This means that silicon may have to be replaced, in some cases, in order for electronics to be woven into clothing for instance. Polymeric or plastic materials are used everyday in life, from plastic cups to mobile phones. Amongst its advantages are that they are flexible, lightweight, strong and have a low cost of production. These four properties stated, in particular the fact that they are flexible unlike silicon, make them perfect for wearable electronics. In general, people think of plastic, as a material that does not conduct electricity. While this is generally true, one category of plastics is quite conductive. This plastic may not be as conductive as silicon, let alone copper, but many applications do not require a material that conducts that well but instead requires other characteristics like flexibility. Conductive plastics are the first step to the plastic chip and many other applications. Currently the main display technology used in portable electronics today is the LCD (liquid crystal display) screen. Its main disadvantages (in terms of wearable electronics) are that it is neither flexible nor lightweight. Moreover it can be bulky its visibility is poor when viewing from angles. Much research, with Philips at the forefront, is being undertaken on the PolyLED (a plastic LED). The PolyLED has three major advantages over its silicon counterpart: it has a high contrast, a high brightness and requires much less power. Although in its infancy, these very three properties along with the prospect of a flexible and rollable display makes it viable for use in wearable electronics, in a way the LCD screen cannot compete. The above Silicon and better plastic transistors might be incorporated into clothing, but they still need to be connected together on the garment of whatever the wearable electronic device is placed on it. Aluminum and/or copper could still be used but having them integrated into garments for instance might not feel very comfortable while plastic might be wasteful because of its higher resistance, even for the best plastics. Using conductive fabrics instead, such as silk organza shown below could solve this.

1.3. Wearable sensors/systems applications

An obvious example is the use of ambulatory systems for ECG monitoring, which has been part of the routine evaluation of cardiovascular patients for almost three decades. However, ambulatory systems are not suitable when monitoring has to be accomplished over periods of several weeks or months, as is desirable in a number of clinical applications. They take advantage of hand-held units to temporarily store physiological data and then periodically upload that data to a database server via a wireless LAN or a cradle that allow Internet connection. The data sets recorded using these systems are then processed to detect events predictive of possible worsening of the patient's clinical situation or they are explored to assess the impact of clinical interventions. Multiple investigations have now reported that such diurnal changes in heart rate and, perhaps more important, variability in heart rate over a 24-hour period are an important indicator of disease evolution and progression [4,5]. Systemic blood pressure serves as a further example of a measurement that is even more useful to the clinician when measured continuously by wearable devices. Several investigations have shown that the pattern of blood pressure over a 24-hour period may be a more sensitive indicator of presence of disease, such as essential hypertension, as well as a more accurate predictor of outcome and end-organ damage [6,7]. An example to measure blood pressure continuously via wearable device is the ring sensor. In Section 2, the ring sensor will be described briefly. The result of several years of work in MIT (Massachusetts Institute of Technology), is a pulse oximetry sensor that allows one to continuously monitor heart rate and oxygen saturation in a very unobtrusive way.

2. Wearable photoplethysmographic ring sensor and applications

WBS (wearable biosensors) could play an important role in the wireless surveillance of people during hazardous operations (military, fire fighting, etc.), or such sensors could be dispensed during a mass civilian casualty occurrence. Given that CV (cardiovascular) physiologic parameters make up the "vital signs" those are the most important information in emergency medical situations, WBS might enable a wireless monitoring system for large numbers of at-risk subjects. On a daily basis, wearable CV sensors could detect a missed dose of medication by sensing untreated elevated blood pressure and could trigger an automated reminder for the patient to take the medication [8].

Ambulatory systems for arterial blood pressure (ABP) measurement exist. A common WBS solution for 24-hour monitoring of ABP involves a portable version of the common oscillometric cuff that fits around the upper arm. This solution requires that the patient keep the monitored arm immobile while the cuff inflates for measurements. By report, this solution has been known to interfere with the sleep and other activities of monitored subjects (and has been reported to cause bruising of the arm at the cuff site).

Another measurement instrument to monitor blood flow, blood volume is photoelectric plethysmography, also known as photoplethysmography is a non-invasive method to detect cardiovascular pulse wave that propagates through the body using a light source and a detector. Photoplethysmography is easy to set up, simple to use and low in cost. In addition, photoplethysmography has the ability to take measurement without having direct contact with the skin surface.

2.1. Basic construction

The ring sensor is an ambulatory, telemetric, continuous health-monitoring device. This WBS combines miniaturized data acquisition features with advanced photoplethysmographic (PPG) techniques to acquire data related to the patient's cardiovascular state using a method that is far superior to existing fingertip PPG sensors [9]. In particular, the ring sensor is capable of reliably monitoring a patient's heart rate, oxygen saturation, and heart rate variability. This device optically captures the pulsation and oxygen saturation of the arterial blood flow, and transmits the signals to a host computer via a radio frequency (RF) transmitter. Fig. 1 shows a conceptual diagram of the ring sensor [10,11].

The ring sensor consists of optoelectronic components, a CPU, a RF transmitter, a battery, and a ring chassis. The optoelectronic components, i.e., micro photodiodes and LEDs, detect the blood-volume waveforms and oxygen saturation level at the patient's digital artery. The CPU controls the LED lighting sequence as well as the data acquisition and transmission process. These signals are locally processed by the on-board CPU and transmitted to a host computer for diagnosis of the pa-

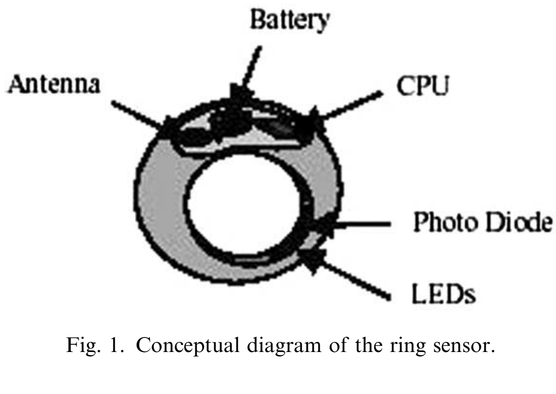

Fig. 1. Conceptual diagram of the ring sensor.

tient's cardiovascular conditions. The ring sensor is completely wireless and miniaturized so that the patient can wear the device comfortably 24 h/day. This miniaturized sensor in a ring configuration is a rational design choice for 24 h continuous monitoring, since a finger ring is probably the only thing that a majority of people will be willing to wear at all times. Other personal ornaments and portable instruments, such as earrings and wristwatches, are not continually worn in daily living. When taking a shower, for example, people remove wristwatches. Bathrooms, however, are one of the most dangerous places in the home. Many thousands of people, mostly hypertensive and the elderly, die in bathrooms every year. Miniature ring sensors provide a promising approach to guarantee the monitoring of a patient at all times. In addition, a ring configuration provides the anatomical advantage of having transparent skin and tissue at the finger compared with other parts of the body so that it is feasible to monitor arterial blood volume at the finger base using an optoelectronic sensor. Subsequently, a variety of simple cardiac and circulatory disorders may be detected by monitoring arterial blood volume at the finger base. Thus, a ring is ideal for long-term measurements [12].

Fig. 2 shows the typical waveform of a photoplethysmograph signal obtained from a human subject at rest. The signal comprises a large segment of

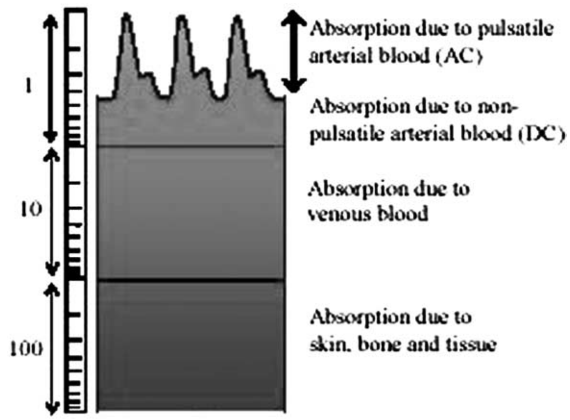

Fig. 2. Illustrative representation of the relative photon absorbance for various sections of the finger. The dc component is significantly larger than the ac component.

dc signal and a small-amplitude AC signal. The dc component of photon absorption results from light passing through various non-pulsatile media, including tissue, bones, venous blood, and non-pulsatile arterial blood. Assuming that these are kept constant, a band pass filter can eliminate the dc component.

2.2. Technical issues

PPG sensors do not meet this premise since, as the wearer moves, the amount of absorption attributed to the non-pulsatile components fluctuates. Power spectrum analysis reveals that this motion artifact often overlaps with the true pulse signal at a frequency of approximately 1 Hz. Therefore, a simple noise filter based on frequency separation does not work for PPG ring sensors to eliminate motion artifact. Furthermore, wearable PPG sensors are exposed to diverse ambient lighting conditions, ranging from direct sunlight to flickering room light. In addition, wearable PPG sensors must be designed for reduced power consumption. Carrying a large battery pack is not acceptable for long-term applications. The whole sensor system must run continually using a small battery. Several ways to cope with these difficulties are

- Secure the LEDs and the photodetector (PD for short) at a location along the finger skin such that the dc component may be influenced less by finger motion.
- Modulate the LEDs to attenuate the influence of uncorrelated ambient light as well as to reduce power consumption.
- Increase the amplitude of the ac component so that the signal-to-noise ratio may increase.
- Measure the finger motion with another sensor or a second PD and use it as a noise reference for verifying the signal as well as for canceling the disturbance and noise.

The location of the LEDs and a PD relative to the finger is an important design issue determining signal quality and robustness against motion artifact. Fig. 3 shows a cross-sectional view of the finger with the ring sensor. The LEDs and PD are

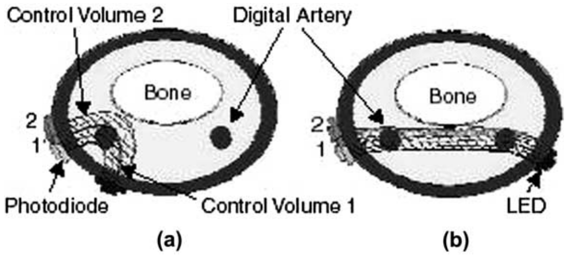

Fig. 3. (a) For the reflective illumination method, movement of the photodiode relative to the LED (position 1 to position 2) leads to a photon path that no longer contains the digital artery. (b) For the transmittal illumination method, movement of the photodetector relative to the LED still contains photon paths that pass through the digital artery.

placed on the flanks of the finger rather than the dorsal and palmar sides. These locations are desirable for two reasons:

- Both flanks of fingers have a thin epidermal tissue layer through which photons can reach the target blood vessels with less attenuation.
- Digital arteries are located near the skin surface parallel to the length of the finger. It should be noted that an arterial pulsation is not only.

For these reasons, at least one optical device, either the PD or the LED, should be placed on one lateral face of the finger near the digital artery. The question is where to place the other device. Fig. 3 shows two distinct cases. One case places both the PD and the LED on the same side of the finger base, and the other places them on opposite sides of the finger. Placing both the PD and the LED on the same side creates a type of reflective PPG, while placing each of them on opposite sides makes a type of transmittal PPG. In the figure, the average pathway of photons is shown for the two sensor arrangements. Although the exact photon path is difficult to obtain, due to the heterogeneous nature of the finger tissue and blood, a banana-shaped arc connecting the LED and PD, as shown in the figure, can approximate its average path [13]. Although these two arrangements have no fundamental difference from the optics point of view, their practical properties and performance differ significantly with respect to motion artifact, signal-to-noise ratio, and power requirements [14,16].

Reflective PPG needs more secure attachments of the LED and PD to the skin surface, when compared to transmittal PPG. Once an air gap is created between the skin surface and the optical components due to some disturbance, a direct optical path from the LED to the PD may be created. This direct path exposes the PD directly to the light source and consequently leads to saturation. To avoid this short circuit, the LED light beam must be focused only in the normal direction, and the PD must have a strong directional property (i.e., polarity), so that it is sensitive to only the incoming light normal to the device surface. Such strong directional properties, however, work adversely when a disturbance pressure acts on the sensor bodies, since it deflects the direction of the LED and PD leading to fluctuations in the output signal. As a result, reflective PPG configurations are more susceptive to disturbances.

2.3. Transmural pressure

Increasing the detected amplitude of arterial pulsations (i.e., the ac component in Fig. 2) improves the signal-to-noise ratio of PPG. It is well understood that the application of an external pressure on the tissue surrounding the artery will increase the pulsatile amplitude. Such a pressure reduces the transmural pressure; that is, the pressure difference between inside and outside of the blood vessel. The pulsatile amplitude becomes a maximum when the transmural pressure approaches zero, since the arterial compliance becomes maximal with zero transmural pressure [17,18]. Applying a pressure, however, may interfere with tissue perfusion. Since the device is worn for long periods, the pressure must be kept such that it does not exceed levels that could damage other vasculature [19]. Thus, the mechanism for holding the LED and PD must be designed such that it provides a safe level of continuous pressure, well below the established clinical threshold. Fig. 4 shows the pulsatile amplitude of a finger base PPG for varied pressures generated by a finger cuff. As the cuff pressure increases, the PPG amplitude increases until it reaches a maximum. As the pres-

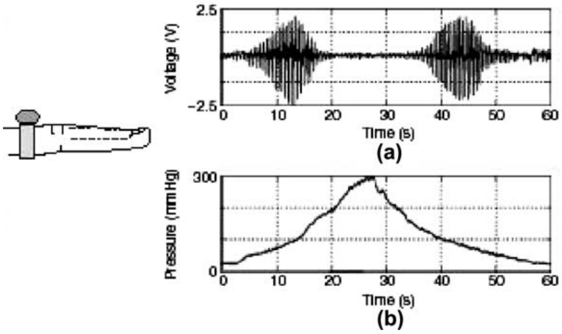

Fig. 4. (a) PPG signal amplitude and (b) pressure at the photodetector.

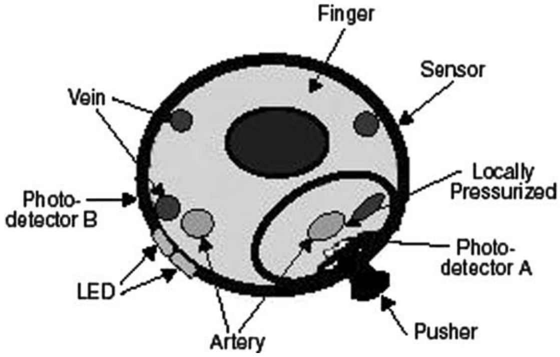

Fig. 5. The schematic of a locally pressurized sensor band.

sure keeps increasing further, the amplitude decreases because of the occlusion of the blood vessels. The cuff pressure yielding the largest PPG amplitude, generally near the mean arterial pressure [20], is too high to apply for a long period. However, to prevent the capillary beds from being collapsed, the cuff pressure must be about 10 mmHg, which is too low to obtain sufficient PPG amplitude.

A solution to this problem is to apply the pressure only at a local spot near the photodetector. When using a cuff or any of the devices that provide uniform surface pressure onto the finger or the arm, it constricts the blood vessels, thus limiting or significantly impeding the amount of blood supplied downstream. However, by providing a local, non-circumferential increase in pressure near the sensor's optical components, it is possible to amplify the plethysmograph waveform while avoiding the potentially dangerous situation of long-term flow obstruction. As shown in Fig. 5, the tissue pressure near one of the arteries can be increased with use of a special mechanism pushing Photodetector A toward the skin. This mechanism, which is attached to the sensor band, would change the pressure distribution such that the transmural pressure of one of the arteries could be high enough to obtain a large pulsatile signal while keeping the pressure low elsewhere to allow for sufficient blood perfusion. As long as the pressurized area is small enough to perfuse it from the surrounding tissue, the local pressurization causes no major complication although the pressure is applied for many days.

3. Smart textiles

The future trend in wearable computing is to integrate electronics directly into textiles. Before going further we have to keep in mind that advanced materials such as breathing (air conditioning), fire-resistant, ultra-strong fabrics are not considered as intelligent (smart), no matter how high technological features they might have. Intelligence is described in the Encyclopedia Britannica as ability to adapt effectively to the environment, either by making a change in oneself or by changing the environment or finding a new one. (...) Effective adaptation draws upon a number of cognitive processes, such as perception, learning, memory, reasoning, and problem solving. 'Smart textiles' are context-aware textiles which are able to react and adapt to stimulus from their environment by integration of smart materials into its structure. The stimulus can have an electrical, thermal, chemical, magnetic or other origin. On principle, two components have to be present in the textile structure in order to bear the full mark of smart textiles: a sensor and an actuator. Design-state space for smart textile and their applications is huge. Initially smart textiles (i.e. E-textile) will find applications in the fields where the need for monitoring and actuation can be vital importance, such as medical environment, military, space travel. Causal clothing is also possible which is expected to be functional as well as fashionable. In daily use of E-textiles, the comfort is even more critical. The first generation of intelligent clothes uses conventional materials and components and tries to adapt the textile design in order to fit in the external elements. A typical example of this is the Philips and Levi's collaboration [21]. It is a jacket with fully integrated communications and entertainment system (earphones, microphone, remote control, mobile phone, mp3 player). No matter how strongly integrated, the functional components remain non-textile elements, meaning that maintenance and durability are still important problems.

Basically, four functions can be distinguished in an intelligent suit: Sensors and actuators, textile processing, power supply storage and communication. They all have a clear role, although not all intelligent suits will contain all functions. They all require appropriate materials and structures and they must be compatible with the function of clothing: comfortable, durable, resistant to regular textile maintenance processes and so on.

3.1. Sensors and actuators

One can use textiles to transform signals in two ways:

Sensor: Transformation of physical phenomena into processable electrical signals.

Actuator: Transformation of electrical signals into physical phenomena.

Sensors can be used to measure biometric or environmental data but also to act as an input interface. Actuators can adapt themselves to a situation, affect the human body or serve as a display.

SOFTswitch [22] is one example of a textile pressure sensor. It is made of conductive fabrics with a thin layer of elasto resistive composite that reduces its electric resistance (resistive change) when it is compressed as shown in Fig. 6.

Another solution has two conductive fabric layers separated by a non-conductive layer, where pressure can create a contact in the holes of the mesh in the middle layer. In the Wearable Motherboard [see section IV], plastic optical fibers detect damage (broken paths) in the fabric and can give information about the location of e.g. bullet penetration. These sensors can also be made to detect chemical, biological and thermal hazards. So-called 'electro active polymers' [23] and can be used as sensors or actuators. France Telecom [24] developed a display made of optical fibers woven into a fabric. The pixel number was just 64 and the fiber diameter 0.5 mm due to the mechanical limitations of the optical fibers. Textile displays also can be realized with conductive fibers covered with a fine layer of an electroluminescent material. Actuators respond to an impulse resulting from the sensor function, possibly after data processing. Actuators are similar to sensors in that they also transform the impulse signal into a respond signal. Shape memory materials are the best-known example in this area. They transform thermal energy into motion. The Italian firm, Corpo Nove, in co-operation with d'Appolonia, developed the Oricalco Smart Shirt [25]. The shape memory alloy is woven with traditional textile material resulting into a fabric with a pure textile aspect. The trained memory shape is a straight thread. When heating, all the creases in the fabric disappear. This means

Fig. 6. SOFTSwitch© applications.

that the shirt can be ironed with a hair dryer. Obviously, controlled release opens up a huge number of applications as drug supply systems in intelligent suits that can be also make an adequate diagnosis. Mechanical and chemical actuators are clear examples, but of course, there are many other types of them for a huge number of applications.

3.2. Textile processing

Processing includes arithmetic operations and storage of data. Challenges such as stability, short lifetime, and slow switching speed have recently been over won, to create organic devices like electro active polymer transistors and batteries. (They are actually threads with transistor functionality.) Flexible chips (e.g. silicon) can be attached to textiles but they are not textile themselves.

3.3. Power supply and storage

The power supply is the heaviest part the biggest problem, says Brad Boren at Norrøna [26]. Two of the most known approaches to develop new power supply technologies, are lithium polymer battery and micro fuel cells. Sunlight, body temperature and body motion are alternative energy sources on the body that can be transformed into electrical energy. In addition, in this case, one should differ between flexible and textile, because there are more efforts to mount flexible energy supplies onto textiles than inventing pure textile power supply. Infineon [27] uses the temperature difference between the outside and the inside of clothing, which produce a power of a few microwatts per cm^2. Thin film solar cells can be made on flexible surfaces such as plastics. The flexible solar cell technology has also been adapted to fiber form. The efficiency of these alternative energy sources needs to be improved. Creating components that are wirelessly powered by an electric field in the environment is another interesting approach. Lunar Design [28] has with its BLU jackets predicted a near future with thin, cheap and flexible digital displays. Another object designed by Murray and Allen "seeks to merge the softness of skin with the hard lines of consumer electronics" [29]. Smart suits often need some storage capacity. Storage of data or energy is most common. Sensing, data processing, actuation, communication, they usually need energy, mostly electrical power. Efficient energy management will consist of an appropriate combination of energy supply and energy storage capacity. As mentioned, *energy supply* must be combined with *energy storage*. Batteries are becoming increasingly smaller and lighter. Even flexible versions are available, although less performant. Currently lithium-ion batteries are found in many applications.

3.4. Communication

For intelligent textiles, communication has many faces, communication may be required: Within one element of the suit, between the individual elements within the suit, from the wearer to the suit to pass instructions, from the suit to the wearer or his environment to pass information.

Within the suits, communication is currently realized by either optical fibers, either conductive yarns. They both clearly have a textile nature and can be built in the textile seamlessly. The advantage and disadvantages of both carriers are well known: optical fibers are light and insensitive to electromagnetic radiation. The transport does not cause production of heat. On the other hand, the signals have to be transformed into electrical ones at least at one point. An example for communication with the wearer is pressure sensitive textile materials (i.e. SOFTswitch applications [22]). These ones allow putting in information, provided a processing unit can be interpret the commands. Communication with the wider environment can be realized by wireless connections. This can be achieved by integrating an antenna. This step is also taken to manufacture this antenna to the textile material. The advantage of integrating antennas in clothing is that a large surface can be used without the wearer being aware of it.

4. Wearable motherboard

The future trend in wearable computing is to integrate electronics directly into textiles. The approach is to use conductive textiles for signal transmission. The electrical performance of textile transmission lines and methods for measuring as well as for modeling the high frequency properties of textiles will be investigated in this section. With the results, it is possible to predict the electrical properties of different textiles and to optimize the fabrics and the signal line configurations. Humans prefer to wear textiles, as they are flexible, soft, lightweight, breathable, robust and washable. These textile characteristics strongly differ from the properties of conventional electronics. The special geometrical and mechanical properties are not only challenging researchers but also offer new fascinating possibilities in creating information systems [30,31]. Therefore, the idea emerged to develop smart fibers and fabrics that can be used for electronic functions. Advances in textile technology and material science have lead to new possibilities in the area of conductive textiles. More recently, the design and realization of the Georgia Tech Wearable Motherboard represents a significant advancement in the integration of textiles and computing paving the way for the paradigm of "fabric is the computer" [32,33].

4.1. E-textile vision

Fig. 7 depicts the vision for "E-Textiles" or the paradigm of "fabric is the computer". The major facets illustrate the various "building blocks" of the system that must be seamlessly integrated to realize the vision, starting with the underlying physical fabric or "Platform". The design of this platform or infrastructure involves the exploration of materials, structures and manufacturing technologies. The second key facet for realizing this paradigm of a true computational fabric is the "Interconnect Architecture" in the fabric, which involves the design and incorporation of physical data paths and interconnection technologies, i.e., the realization of "textile electrical circuits." Integration of sensors, microchips and other devices (e.g., for communication and control) is critical for the realization of an "intelligent" E-textiles for any application, say for example, battlefield management, and therefore, "Hardware Integration" constitutes the third facet or building block shown in Fig. 7. Issues related to information processing such as fault tolerance in light of manufac-

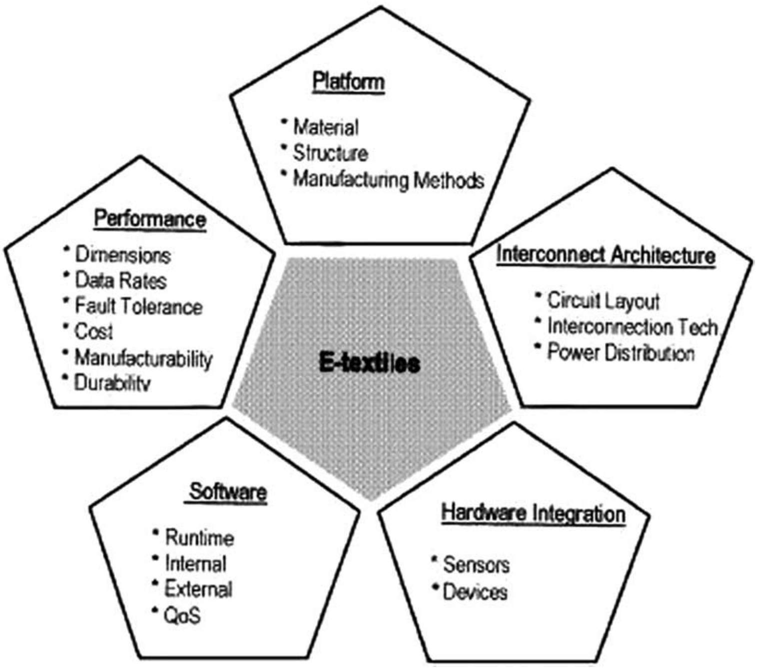

Fig. 7. E-textile vision.

turing defects and Quality of Service (QoS) within the E-textile and between the E-textile and external agents/devices are critical for the incorporation and optimal utilization of computing resources, and therefore, "Software" is the fourth facet of the E-textile continuum. And finally, as shown in the figure, a set of underlying performance metrics ranging from the physical dimensions (of the resulting structure/system) to costs, manufacturability and data flow rates must be utilized to assess the successful realization and performance of the desired E-textile. Thus this paradigm of "fabric is the computer" represents a fascinating area of research that fosters, nay necessitates, collaboration amongst scientists and engineers from a variety of disciplines including textiles, computing and communications, sensor technologies and application domains (e.g., medicine, space, military) [34].

4.2. The wearable motherboard

The Georgia Tech Wearable Motherboard (GTWM) provides an extremely versatile framework for the incorporation of sensing, monitoring and information processing devices. It uses optical fibers to detect bullet wounds, and special sensors and interconnects to monitor the body vital signs of individuals [35].

The third generation Georgia Tech Wearable Motherboard™ is shown in Fig. 8.

Fig. 8. Georgia Tech Wearable Motherboard™.

This design was woven into a single-piece garment (an undershirt) on a weaving machine to fit a 38–40″ chest. 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 using a novel modification in the weaving process. With this innovative deign, 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 weaving machine.

In Fig. 9, the EKG trace from the Wearable Motherboard is shown along with the control chart produced from a traditional set-up. Similarly, the wearer's temperature has been monitored using a thermistor-type sensor. A subject wearing the Georgia Tech Smart Shirt 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, a fully functional and comfortable wearable motherboard has been designed, developed and successfully tested for monitoring vital signs [36].

4.3. Realization of architecture

The first step in realizing the architecture through a prototype demonstration has been to define an ideal switchbox element that we believe is buildable using current technology. The next step is to begin prototyping an approximation to the ideal device to serve as a proof-of-concept. The ideal device is an EEPROM-based FPGA in a custom plastic package that contains insulation-displacement-style connectors instead of pins. The device would be press-fit onto the fabric like a fastener. Once configured, the device would provide digital communications between points on the

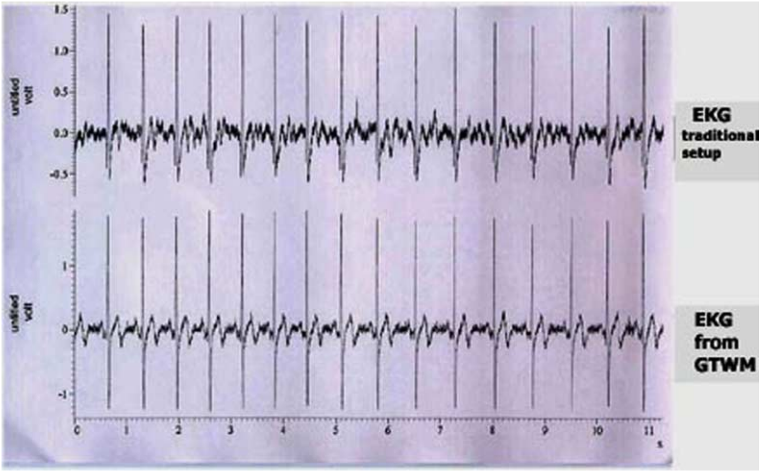

Fig. 9. EKG waveforms from traditional setup (above) and GTWM (bottom).

fabric including sensors, effectors and communications devices that attach to the switchboxes or directly to conductive fibers that cross a switchbox. The prototype device is a 2.8″ × 1.8″ protoboard containing a small EEPROM-based FPGA (Altera EPM7160S) plus a microcontroller (Motorola HC11) as shown in Fig. 10. The board connects to the fabric using two standard 26-pin insulation displacement connectors (IDCs) ordinarily used for ribbon cable. The fabric in Fig. 10 contains conductive fibers at a density of 10 per inch. The 26-pin IDCs contain contacts at a pitch of 20 to the inch. We find that every fiber makes contact with some contact in the connector but the position of that contact is off by up to two positions in the connector. In the connector, the leftmost and rightmost fibers are dedicated to power buses while the center fibers carry signals, up to seven signals in each direction.

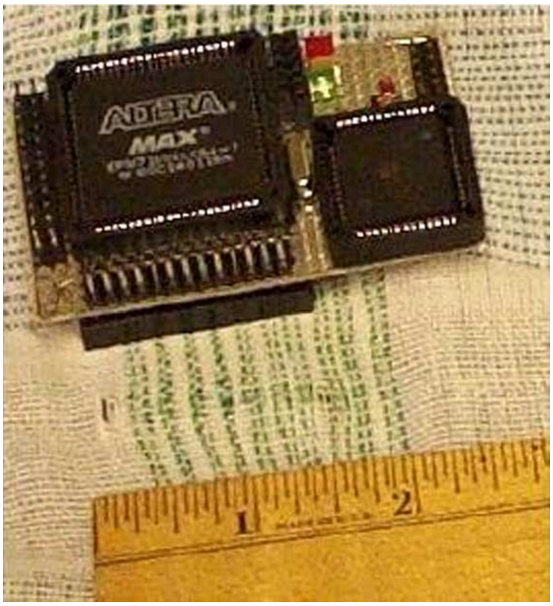

Fig. 10. Prototype board, 2.8″ × 1.8″, containing the FPGA and microcontroller.

The chosen FPGAs were physically integrated into the fabric (see Fig. 4-07). Software was developed to demonstrate the "in-fabric" network. One of the FPGAs communicated with an external agent (a Linux-based personal computer) that was responsible for managing the global configuration of the FPGAs in the fabric by sequencing the "discovery" in the fabric beginning with that initial FPGA. Two software modules were created; the first was to "demonstrate" the pin-connection discovery algorithm implemented in the system to identify the connections between the various pins on the FPGAs in the fabric and to display the connection paths. This enables discovery of the interconnects on the fly after the manufacturing has been carried out and there is no a priori knowledge of the specific connections between the elements in the fabric. The second module discovers the connections and displays the paths on the screen as the discovery process proceeds when the FPGA is powered. To demonstrate the flow of information in the fabric network through the soft interconnects, a potentiometer was attached as a daughterboard to one of the FPGAs and whenever it was "twiddled" as shown in Fig. 10 [37].

5. Electroactive fabrics and wearable biomonitoring devices

Promising recent developments in material processing, device design and system configuration have enabled the scientific and industrial community to focus their efforts on the realization of smart textiles. In fact, all components of interactive electromechanical systems (sensors, actuators, electronics and power sources) can be made from polymeric materials, to be woven directly into textile structures (sensing and actuating micro-fibers) or printed or applied onto fabrics (flexible electronics). In particular, intrinsic sensing, actuating, dielectric or conductive properties, compliance, lightness, flexibility and the relative low cost of many electroactive polymers make them potentially suitable materials for the realization of such systems.

The aim of this section is to give a picture of the potential use of smart materials in the realization of sensing strain fabrics and of actuating systems. In particular, the early stage implementation and preliminary testing of fabric-based wearable interfaces are illustrated with reference to a functionalized shirt capable of recording several human vital signs and wearable motion-capture systems [38].

5.1. Materials and fabric preparation

Different fabrication methods have been used to give piezo-resistive properties to garments. The first approach involves coating conventional fabrics with a thin layer of polypro (PPy), a Π-electron conjugated conducting polymer, which combines good properties of elasticity with mechanical and thermal transduction.

Sensors based on carbon-filled rubber (CFR) were realized either by directly printing the carbon/rubber mixture onto fabrics or by weaving CFR coated fibers. Threads and fabrics of this type have been obtained as an experimental product.

5.2. Sensing and actuating fabrics

The characterization on PPy-coated fabrics has pointed out a gage factor of about -13 (negative and similar to nickel) and a temperature coefficient of resistance (TCR) of about 0.018 $°C^{-1}$. Despite the fact that high GF value is suitable for strain gage implementation, two serious problems affect PPy coated fabric sensors. The first problem resides in the strong variation with time of the sensor resistance. The second problem is the high response time of the sensors; in fact after sudden application of a mechanical stimulus, the resistance reaches steady state in several minutes; this makes these fabrics unusable in most applications.

Electroactive polymer actuators are being studied and developed to be embedded into fabrics, and to endow fabrics with motor functions. Three kinds of electroactive materials (conducting polymers, dielectric elastomers and carbon nanotubes) are under investigation. Conducting polymers (CP) show a drastic change in electrical conductivity and in the dimensions associated with changes in ionic doping inside the polymer. For these characteristics, conducting polymers are potentially useful in several fields of applications. There are two main groups of applications for these polymers. The first group utilizes their conductivity as its main property. The second group utilizes their electro activity. The extended π-systems of conjugated polymer are highly susceptible to chemical or electrochemical oxidation or reduction. These alter the electrical and optical properties of the polymer, and by controlling this oxidation and reduction, it is possible precisely control these properties. Since these reactions are often reversible, it is possible systematically control the electrical and optical properties with a great deal of precision. It is even possible to switch from a conducting state to an insulating state [39]. The two groups of applications are shown below:

Group 1: Electrostatic materials, conducting adhesives, electromagnetic shielding, printed circuit boards, artificial nerves, antistatic clothing, piezoceramics, active electronics (diodes, transistors), aircraft structures.

Group 2: Molecular electronics, electrical displays, chemical, biochemical, and thermal sensors, rechargeable batteries and solid electrolytes, drug release systems, optical computers, electromechanical actuators, smart structures switches.

In particular, it has been shown that conjugated electroactive polymers can exert high forces, much greater than those of natural muscle and that they undergo volume changes with noticeable variations of elastic moduli when ionic species are forced to penetrate inside their network by electro diffusion. The electroactive polymers are usually based on materials that respond to an applied electric field (as opposed to charge or mass transport). Moreover, carbon nanotube actuative fibers have been made and preliminarily characterized as actuators. Their projected superior mechanical and electrical properties (high actuating stresses, low driving voltages and high energy densities) suggest that superior actuating performances can be expected [40]. The technique is quite new, and the processing of carbon nanotube materials is a key factor for improvements.

5.3. Wearable monitoring devices

An emerging concept of healthcare, aimed at a continuous monitoring of vital signs to provide assistance to patients, is gaining wider consensus [41]. Advances in both sensor technology and communication technology and data treatment form the fundamental basis for a new generation of healthcare assistance systems.

The use of 'intelligent materials' enables the design and production of a new generation of garments with distributed sensors and electrodes [42,38]. Wearable non-obtrusive systems will permit the user to perform everyday activities with minimal training and discomfort.

A shirt was functionalized with CLR piezoresistive fabric sensors, used to monitor respire trace (RT), and conductive fabrics, used as electrodes to detect electrocardiogram (ECG) as shown in Fig. 11.

To record the ECG signals, two different square-shaped fabrics (1×1 cm) were used: the first was made with steel threads wound round acrylic yarns, the second with a layer of acrylic/cotton fabric coupled with a layer containing stainless steel threads. In order to assess their performances, the signal originating from an Ag/AgCl electrode (Red Dot by 3M) was recorded simulta-

(a) (b)

Fig. 11. Positioning of fabric sensors on a smart shirt for RT (a) and ECG (b).

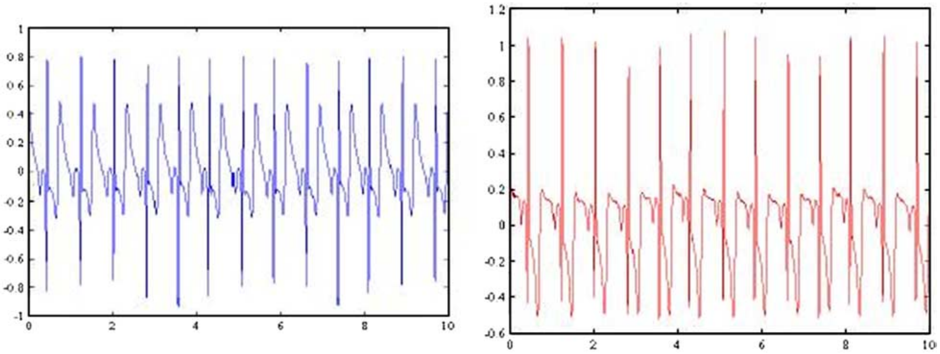

Fig. 12. (a) ECG detected with bi-layer fabric and (b) ECG detected with standard electrode.

neously with the signal detected by the fabric electrode. The electrodes were applied at positions V4 and V5; the configuration used is shown in Fig. 11b. The comparison of the two signals for the bi-layer fabric and the standard electrode is reported in Fig. 12a and b. The frequency and amplitude of the response of the fabric electrode were similar to those of the standard one.

6. Results

It is evident that, biomedical sensors will keep improving. They have a great, in many cases even vital, contribution to human health. The biomedical sensors, as being an integral part of biomedical devices, will continue to be a prosperous market segment. This suggests an ever-evolving trend coupled along with innovation.

The biomedical sensors are also suitable and applicable for a broad spectrum of monitoring purposes in risky environments. We have every reason to believe in that, military, security and human intelligence adaptations will give an enormous impact.

Biomedical sensors will also find a way for entertainment adaptations. Entertainment is a big sector, including sports and leisure time activities. In this more health conscious world, there will be broad application area. For example, mountain climbers, divers and even cross country bikers will be very eager to being monitored for any emergency.

Actually, biomedical sensors will be an integral part of modern world; dubbed as wearable, smart, intelligent, or whatever the appropriate nomenclature might be.

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