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DOI
10.1109/EuroSimE.2019.8724586

Publication date
2019

Document Version
Accepted author manuscript

Published in
2019 20th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE 2019

Smart textiles: how electronics merge into our clothing

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Abstract

Smart textiles are textiles with integrated sensors, data processing, communication and power units and can be regarded as a new application field for microelectronic devices. It largely benefits from a series of recent developments: sensors become smaller, more reliable and require less power and, on the other hand, energy harvesting techniques are continuously improving as well as energy storage devices as flexible batteries and super capacitors. Based on these rapid developments it is not unlikely to expect that in the near future we indeed will have textiles with an integrated battery less sensor network which will continuously monitor the health of patients, soldiers or you yourself.

In this paper we show that before these e-textiles are as widely spread and accepted as our cell phones, a number of hurdles must be taken first.

1. Introduction

According to the IdTechEx report [1] the market for e-textiles is currently close to the $100m in annual wholesale revenue and is expected to grow towards the $5 bn in 2027. The key market sectors include Sports & Fitness, Medical & Healthcare, Wellness, Home & Lifestyle, Military, Fashion and Automotive. This rapid growth and spreading over the different market sectors is quite fascinating and calls for a more in depth study on how the sectors of electronics and textiles could merge towards a novel market field.

In the discussion about sensor clothing it is useful to distinguish between wearables and smart textiles. We define wearables (Fitbit like bracelets, rings, ear plugs) as rigid devices with strongly integrated sensors, electronics and power supply which are worn close to the body with the purpose to collect health and activity data. On the other hand, Smart Textiles (or electronic textiles, E-textiles, intelligent textiles) are defined as textile based materials which can sense and interact with the environment. They have a similar strong integration of sensors, electronics and power supply as wearables but in addition are soft and seamlessly integrated in textile products. That means that also the associated electronic parts need to be soft, stretchable and able to resist the washing and cleaning processes commonly used for textiles. An example of a commercial smart textile product are the Sensoria fitness socks, as shown on Fig.1-right. Other examples are mentioned in [12-15].

Figure 1. a) Smart bracelets, b) smart ring and c) Sensoria fitness socks [2]

Examples of smart textiles prototypes developed in our lab at TU Delft are shown in Fig.2. Fig.2a shows a stress vest for veterans with PTSD (Post Traumatic Stress Disorder) which monitors heat rate, temperature and skin conductivity using commercially available off-the-shelf sensors. Such sensors are rigid and need special protection to withstand machine washing which, in the end, often makes the sensor system bulky and uncomfortable. For that reason research was started in developing thin, textile based sensors, for example consisting of conductive and stretchable or non-stretchable tissues. The Globus fitness shirt (Fig.2b) was developed to measure the backbone angle during weight lifting and warn the user when the bending angle was too large. The sensors were embedded at the back side of the shirt and consist of two conductive, non-stretchable fabrics which were attached to stretchable non-conductive fabrics in such a way that upon stretching the electrode overlapping area increased, resulting in a measurable change in capacitance (Fig.2c). Sensors like this are unobtrusive, washable and relatively simple to make. The electronics and data communication unit (Fig.3a and blue part at sleeve of the prototype in Fig.2b) is attached magnetically and should be taken off before washing.

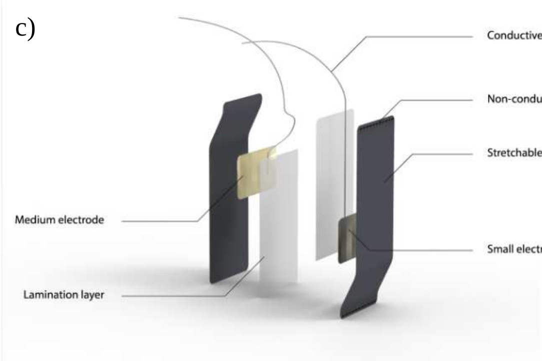


Figure 2. Examples of textile based soft stretch sensors. a) Prototype of stress sensing vest with off the shelf sensors [7; b) Prototype with embedded textile based sensors [8]; c) Textile based stretch sensor [8]

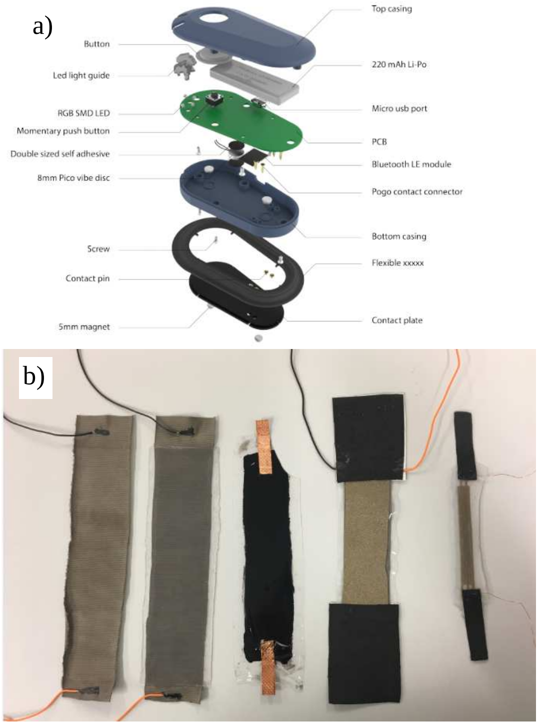


Figure 3. a) Data communication unit of Globus fitness shirt [8]; b) Examples of textile based soft stretch sensors [9]

By combining stretchable textile fabrics and silicon rubber spacers other textile based sensors can be constructed for measuring stretch or local pressure (Fig.3b).

While developing garments with embedded sensors and electronics we always have to deal with the internal wiring system, which in some cases can become quite complex. Fig.4 shows a cooling vest for women with hot flashes [10] which senses a sudden increase of skin temperature (hot flash) and acts by switching on the 18 integrated thermoelectric cooling elements. In order to improve the comfort and facilitate manufacturing it would be desirable to be able to replace the electrical wiring system (Fig.4b) with a textile layer which replaces all the copper wires and onto which the sensors and actuators can be mounted. Such a textile layer will then have a function similar to a Printed Circuit Board and in analogy can be called a “Fabric Circuit Board, as suggested in Li and Tao’s paper [11].

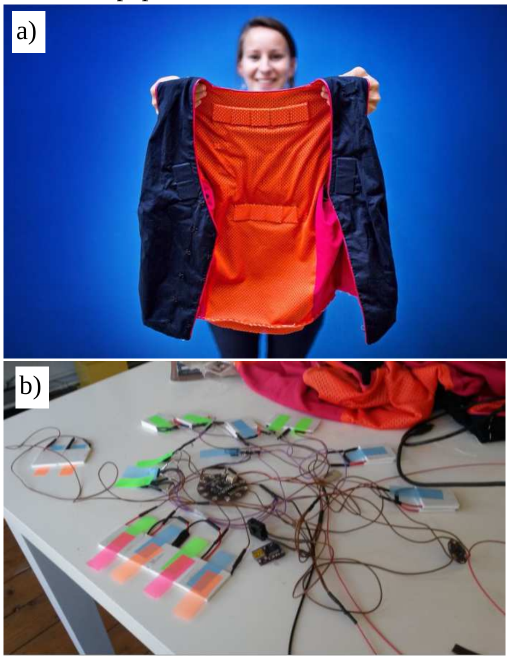
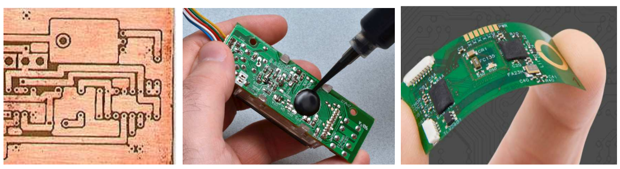


Figure 4. a) Vest with integrated thermoelectric cooling elements and b) the associated wiring system [10]

2. From PCB to Fabric Circuit Board (FCB)

As a matter of fact, we can consider the above mentioned Fabric Circuit Boards as the next step in circuit board evolution. Circuit boards started with copper plated epoxy laminate plates in which conductive traces were etched (Fig.5a). The increasing integration density then called for two and, in the 1990s, multilayer substrate boards (Fig.5b), all of which are still rigid. The use of copper cladded polyimide foils allowed the development of Flexible Printed Circuits (Fig.5c) which are nowadays often used for parts needing flexible interconnect sections. The development of stretchable circuit boards and interconnects started in the early 2000s [12,13] and typically consisted of a silicon rubber substrate with meandering copper structures (Fig.5d). Although stretching level near to 100% could be obtained, the reliability was limited due to plastic yielding in the copper layers. A big step forwards therefore was the recent introduction of a stretchable conductive ink by Dupont [14] which can be simply screen printed on a rubber substrate which can be used as a stretchable interconnect, sensor part or circuit board.



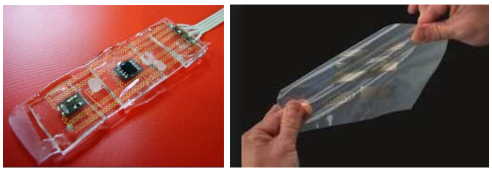


Figure 5. Substrate development from rigid PCB to flex PCB, stretchable silicone rubber [12,13] and stretchable conductive ink on polyurethane [14]

3. Textile interconnect circuits

The idea of integrating conducting wires in textiles with the aim to create a wearable, textile data network goes back to the works of Gorlick [15] and Post et al. [16]. Gorlick prototyped elastic suspenders with embedded copper wiring onto which batteries and sensors could be connected with especially designed connectors. Post, on the other hand, used conductive yarns and an embroidery machine to create sensors and to interconnect a series of electronic components in textiles [16]. Amongst the applications they show are the Firefly dress and the Musical Jacket with a fabric keypad. Later on other researchers followed up. Park et al. introduced the idea of a wearable motherboard with ribbon cables and snap fitting pin connectors [17], whereas Li and Tao used knitted copper wires and a helical spring connection to the sensor elements [11]. An interesting attempt to solve the problem of chip to textile interconnection is proposed by the French CEA-LETI group [18]. These researchers demonstrate the possibility to directly connect conductive (textile) wires to the chip surface. They do this by using MEMS processing steps to produce a chip assembly with spacer slits in which the conductive wires can be inserted (See Fig.6). The technology is currently being developed further by the startup Primo1D which focusses on RFID applications.

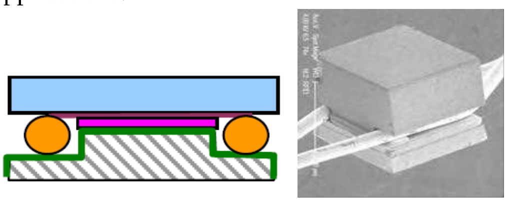


Figure 6. Direct wire to chip connection (the “Diabolo” process) [18]

4. A plan for the next generation of E-textiles

As mentioned earlier, the first electronic textiles were developed already 2 decades ago, so it is relevant to ask why E-textiles are not widely available yet despite of their many obvious advantages. They have the potential of unobtrusively measure and monitor the state and condition of our body and society seems ready for it: fitness adepts are eager to monitor their health progress, elderly people feel safer knowing that their health is continuously being monitored and revalidation can be more effective with the aid of dedicated sensor textiles. The reasons for the fact that large scale commercial applications are still lacking differ for the different application fields. If aiming at the fitness (gadget) market then reliability is less important but the price is. Although most of the larger companies in the sports clothing market have developed prototypes for smart fitness shirts, it is not yet commercially viable to produce and sell them cost effectively. Smart garments for medical applications like patient health monitoring, on the other hand, can be more expensive but must be comfortable for the patient, easy to apply by the medical staff, cleanable or washable, highly reliable and in some cases go through a long certification process. In addition, prototypes can be readily produced in small numbers but scaling up towards mass production is still a challenge yet. In particular, the integration of the sensors, electronics and wiring into the garment in the current way is too labour intensive. Yet another challenge for the successful introduction of E-textiles is that they have to survive a number of washing machine cycles in which the embedded electronic components are soaked in water, exposed to chemicals (detergents) and are folded heavily.

In the above we have seen that E-textiles have a large potential, that most technologies for it are, in principle, already available but that there are still severe problems with scaling up and with the reliability. Below we will present a possible plan for solving this and enabling the development of a next generation of mass produced, robust and reliable smart textiles.

We propose to choose for the concept of a modular system consisting of a textile part with integrated wiring circuit (the Fabric Circuit Board) and separate sensing and data processing nodes which can be added to the base garment by clicking or snap fitting. In this way the garment with wiring system can be mass produced using well known and mostly already proven textile manufacturing technologies and equipment. Using computer controlled methods for the knitting, printing or embroidery of the conductive circuitry, also different shapes and sizes of the base garment can be readily manufactured. On the other hand, the sensor, energy supply and data processing nodes can be further developed by spin-off companies from the electronics industry such that they form the thin, flexible and soft devices that are required for the future generation of E-textile products. The main problem that then remains is of course the interconnection between the active nodes and the passive Fabric Circuit Board. Such interconnections need to be robust, reliable and above all, standardized. This will not be easy but is in principle possible considering the experience and expertise with interconnect technology that is available in the microelectronics domain.

A modular electronic garment as proposed here will have several additional advantages. Sensor nodes which are malfunctioning or outdated can be simply replaced individually without the need to discard the entire garment. Changing, updating or adding sensors can then be done in a similar way as we currently work with apps on our mobile phones. Moreover, with such a garment the electronic components can be easily separated from the textile part at the end-of-life.

In order to further develop such a modular system both the textile industry and the electronics industry should invest in developing new technologies. We need to:

- Develop standardized reliability tests for electronics in textile applications (washing tests, foldability and mechanical wear). Both for the separate components and the total system
- Develop and standardize interconnections between electronics, sensors and the conductive circuit on the textile
- Design, develop and standardize manufacturing technologies for the base garment with embedded circuitry (the Fabric Circuit Board)
- Develop assembly lines for the placement of the electronics and sensor nodes onto the garment

All these required technology steps are in itself quite feasible but in order to realize it governments and companies must be willing to invest in it and scientists and engineers from different disciplines must cooperate intensively. If we manage to do so, we can prepare for a future in which we wear a smart shirt which take care of us, monitors our health and warns us if needed.

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