

Woven Electronic Textiles: An Enabling Technology for Health-care Monitoring in Clothing

Christoph Zysset, Thomas Kinkeldei, Kunigunde Cherenack, Gerhard Tröster
Wearable Computing Group, ETH Zurich
{zysset, kinkeldei, cherenack, troester}@ife.ee.ethz.ch

ABSTRACT

In this work we present a technology to integrate electronic devices into textiles at the yarn level. This enables the fabrication of electronic textiles that remain bendable and are therefore suitable for sensor integration into clothing (e.g. to measure physiological signals). This technology is applied to integrate digital silicon based temperature sensors into a textile band which is then combined with an undershirt to measure the temperature between skin and clothing. This temperature can be used as an indicator for heat stress experienced by people in high-risk professions, athletes and dementia patients. We demonstrate the capability of this technology by using this undershirt in a 4 hour measurement and a protective clothing scenario.

Author Keywords Wearable sensors; Textile integration

ACM Classification Keywords J.2 [Physical Sciences and Engineering]: Electronics. J.3 [Life and Medical Science]: Health.

General Terms Experimentation, Measurement

INTRODUCTION

The combination of electronics and textiles provides an ideal platform for ubiquitous sensing in sports, health care and high-risk professions. Here we present a novel method to integrate electronic devices and interconnections into textiles. The main advantage of this approach is that the textile remains bendable. The method is demonstrated by fabricating a temperature sensitive textile ribbon which is integrated into an undershirt to measure the temperature between the skin and the clothing layers. Knowledge of this temperature aids in detecting heat stress or undercooling of the body and can potentially be applied in a manifold of scenarios.

A common approach towards integrating electronics into textiles is to measure physiological parameters by attaching a printed circuit board (PCB) to a textile substrate. The PCB serves as substrate for devices such as microprocessors, sensors, data storage units and transmitters [1, 2, 3]. All these approaches suffer from the drawback that the PCB transfers its rigidity to the textile substrate preventing the fabric from bending.

The ability of a textile to bend is essential for the drape of

the fabric and ultimately for clothing [4]. The integration of electronics into textiles while still allowing the textile to bend and wrap around the body can promote the realization of smart garments and undergarments. The use of smart undergarments to monitor patients has been suggested but not realized [5].

Integrating sensor devices in undergarments enables the measurement of the temperature between the skin of a human body and the clothing layers, and can support physiological monitoring of people in several research fields: professionals in high-risk occupations that are required to wear heavy protective clothing, dementia patients that misjudge the weather and therefore dress inappropriately and athletes that need to dissipate an increased amount of heat during physical activity. All of these groups can suffer from heat stress and heat stroke [6, 7]. Heat strokes are caused when the core temperature of the human body rises up to temperatures between 40 °C and 42 °C [8, 9]. This increase of the body temperature occurs when the dissipation of energy is hindered by an increased temperature and humidity of the environment causing the body to store heat and ultimately leading to a heatstroke [10].

TECHNOLOGY

The technology to integrate electronic devices into textiles is based on flexible plastic substrates with electronics combined with the inherent X-Y grid structure of a woven fabric. Weaving involves two distinct types of yarns or threads, called warp and weft (see Figure 1), which are interlaced at right angles to form a fabric [11]. The warp yarns run lengthwise through the weaving machine and the weft yarns are woven into the warp yarns. We make use of the arrangement of the two yarn types in our technology as follows:

- Conductive yarns are integrated into the textile in the warp direction.
- Flexible plastic fibers with integrated electronic functionalities are woven into the textile in the weft direction.
- The conductive yarns in the warp direction are used to connect the electronic circuits on the flexible plastic fibers.

The approach of replacing several warp yarns with conductive threads and a part of the weft yarns with

functionalized flexible plastic fibers results in a woven fabric in which electronic functions are added at the yarn level. The whole process of integrating conductive yarns and flexible plastic fibers is compatible with commercial weaving machines. Figure 1 shows a schematic of the resulting electronic textile. The three wide strips in weft direction represent the flexible plastic fibers and the integrated electronic functionality as black squares. Four warp yarns indicate the conductive threads and the black dots represent contact points between electronic circuits on the flexible plastic fibers and the conductive threads. The remaining dark gray and white yarns are standard textile yarns in weft and warp direction.

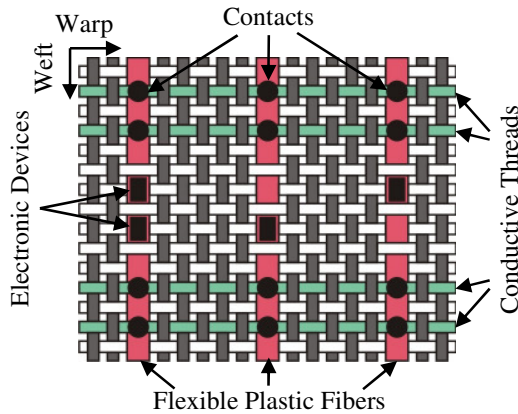


Figure 1. Schematic of a woven textile with warp yarns in white and weft yarns in dark gray. The wider fibers correspond to the plastic fibers with integrated electronics and four warp yarns are replaced with conductive threads. The black dots symbolize the contact between conductive yarn and plastic fiber.

This smart textile fabrication approach offers several advantages:

- Flexible plastic fibers can serve as substrates for a variety of electronic components: thin-film devices ranging from single transistors to complex circuitry consisting of multiple material layers, interconnect lines, sensors and contact areas (to connect the electronics on the plastic fiber to the conductive threads in Figure 1) processed out of a single material layer and attachment of bare die chips.
- The electronic components can be randomly distributed over the whole flexible fiber by selectively patterning the material layers on the substrate.
- The distance between two adjacent flexible plastic fibers can be chosen freely.
- The use of flexible substrates for the electronics in weft direction and the conductive threads in warp direction improve the ability of the textile to drape, compared to rigid PCBs attached to textiles.
- Plastic substrates are scalable to industrial processes like the roll-to-roll technique.

These advantages enable us to choose the location of the integrated electronics in the textile as well as their functionality while maintaining fabric drapability.

The X-Y structure of electronics carrying fibers in weft direction and conductive threads in warp direction favors bus and array structures. This in turn allows the integration of different modalities in a single textile and selective access to them via bus lines.

Figure 2 shows a prototype of a textile with temperature sensitive electronic devices on woven plastic stripes. This textile is woven on a commercial weaving machine and based on the technology described here.

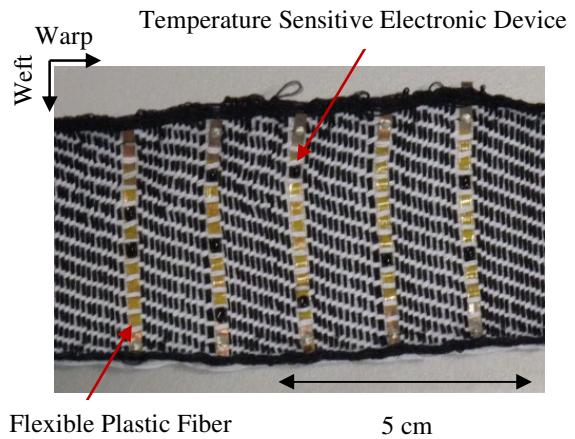


Figure 2. Prototype of woven textile with integrated electronics.

TEMPERATURE SENSITIVE UNDERSHIRT

To enable the measurement of the temperature between skin and clothing layers, a temperature sensitive undershirt was produced. First, a temperature sensitive textile patch, shown in Figure 2 was made. Five 2 mm wide and 4.5 cm long plastic fibers with contact areas for the conductive threads and with attached bare temperature sensor chips (DS18S20 from Maxim-IC) were fabricated. The temperature sensors are silicon based devices and can operate using a 1-Wire bus protocol. This allows us to interface with the sensors on all chips by connecting them with only two wires: one for ground and the other one for power and digital signal transmission. Therefore the textile contains two conductive threads in warp direction to access all the sensors. As can be seen in Figure 2 the temperature sensors are randomly distributed on the flexible plastic fibers.

The textile patch is then integrated into an off-the-shelf cotton undershirt. The undershirt worn by a manikin and the inside of the undershirt are shown in Figure 3 (a) and (b), respectively.

The two conductive threads of the temperature sensitive textile patch are routed to the outside of the shirt and attached to two snap fasteners. With these snap fasteners data logging devices such as a lap-top can be connected.

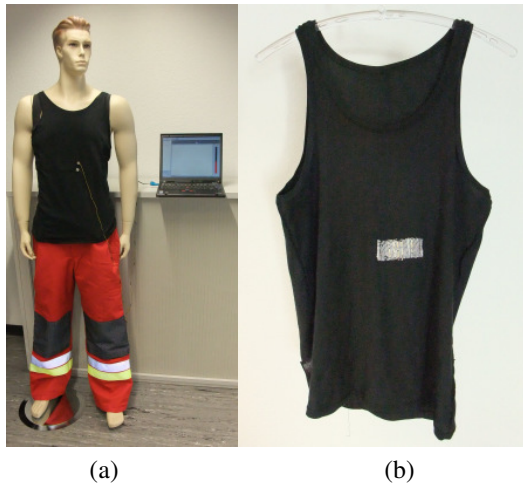


Figure 3. (a) a manikin wearing the undershirt connected to a lap-top to log the temperature, (b) the inside of the undershirt with the temperature sensitive textile patch.

EXPERIMENTAL

Mechanical Stability

The mechanical stability of the contacts between conductive warp threads and flexible fibers with the temperature sensors was tested by applying shear forces. We tested the mechanical connections with forces up to 20 N and could not locate a failure. Instead the flexible substrate started to deform because the forces were transferred to the flexible plastic fiber. A force of 20 N is well above the 8 N a single finger tip can exert and therefore the sensor performance remains stable even when the temperature sensors or the contacts are touched while wearing the smart textile [12].

Textile Flexibility

We measured the minimal bending radius that the textile can be exposed to and the bending rigidity. We bent the textile down to a radius of 0.75 mm along the weft and the warp yarns without observing an error in the sensor signals. An error occurs only when the textile is folded so that the ground yarn touches the power/signal thread. This can be prevented by using isolated conductive threads in warp direction.

The bending rigidity is a parameter used in the textile community to quantify the ability of a textile to bend [4]. The integration of the conductive threads and the flexible plastic fibers in weft direction decreases the ability of our textile to bend by around 30 %. Still, the bending rigidity remains at the same order of magnitude obtained for commercially used clothing fabrics [13].

Temperature Measurement

To demonstrate the ability of the undershirt to monitor the temperature between skin and clothing layers, two experiments were conducted. In the first experiment, subjects were first asked to relax and then had to put on a firefighter jacket. In the second experiment, the temperature

between the skin and the clothing layers was monitored for a period of four hours.

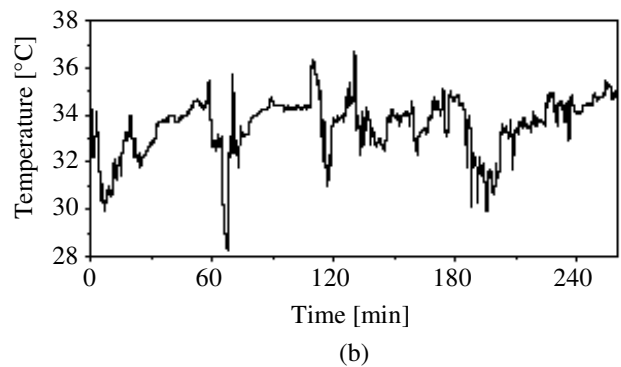
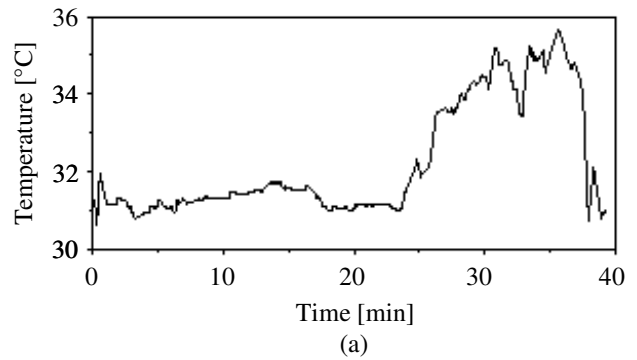


Figure 4. Temperature measurements between skin and clothing layers (a) until minute 23 the subject was relaxing, then it put on a firefighter jacket, (b) long term measurement of temperature between body and clothing layers.

In Figure 4 (a) the subject was sitting at its desk until minute 23. Then he put on a firefighter jacket and performed some push-ups. The produced heat was stored between the clothing layers and the skin. The downwards spike at minute 33 was caused by ventilating the jacket resulting in a decrease of temperature [14].

The long term temperature tracking is shown in Figure 4 (b). The subject was wearing the temperature sensitive undershirt and a cotton shirt over it. Except at minute 70 where the subject went outside the building, the subject was sitting at his desk, walking around in the building or talking to co-workers. The variations observed in the temperature curve are caused by movements of the subject, resulting in exchange of the air between clothing and skin.

The first experiment shows that an increased temperature that was caused by changing the subject's clothing can be detected. The second experiment shows that our temperature sensitive undergarment can be used for long term temperature measurements without restricting the subject's behavior. This is important for applications in the health care sector where monitoring patients over time is required.

Wearability

To evaluate the wearability and comfort of the smart undergarment 7 subjects were asked to wear the shirt and fill out a questionnaire. They were asked the following two questions:

1. On a scale from 1 to 5: Does the shirt hinder you in your freedom to move? 1 stands for “I cannot move anymore” and 5 “I can move as freely as with normal clothing”.
2. On a scale from 1 to 5: Does the undershirt feel comfortable? 1 stands for “it feels totally uncomfortable” and 5 “I do not feel any discomfort”.

The results of the questionnaire are presented in Figure 4. The answers to question 1 show that the integrated electronics in the textile do not restrict the freedom to move. A slight restriction on wearability is caused by two cables required to connect the sensors to the data logging device. The average value (4) obtained for question 2 revealed that the shirt is comfortable. Some wearers reported that the flexible plastic fibers sometimes scrape on their skin.

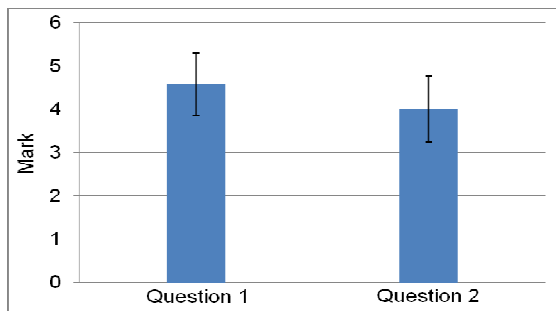


Figure 4. Mean and standard deviation of the results of the wearability questionnaire

CONCLUSION & OUTLOOK

In this paper we described a novel method to integrate electronic components, ranging from thin-film devices and interconnect lines to bare integrated circuits, into a woven textile during weaving.

This approach is used to fabricate a temperature sensitive textile which is then integrated into an off-the-shelf cotton undershirt. The temperature sensitive textile remains bendable and is mechanically stable enough to withstand forces exerted when wearing the textile. Therefore the technology is an ideal candidate for sensor integration in clothing.

The undershirt enables the measurement of the temperature between the skin and the clothing layers. The experiments showed that long term measurements are possible and temperature changes caused by wearing different clothing layers are detectable.

This technology is not only limited to temperature sensors but could be used to incorporate other sensor modalities

such as humidity or acceleration. This in turn opens a wide area of applications in health monitoring, preemptive monitoring and support in rehabilitation.

REFERENCES

1. Park, S., Mackenzie, K. and Jayaraman, S. The wearable motherboard: A framework for personalized mobile information processing (PMIP). In *Proceedings of the 39th annual Design Automation Conference*, ACM (2002), 174.
2. Harms, H., Amft, O., Tröster, G. and Roggen, D. Smash: A distributed sensing and processing garment for the classification of upper body postures. In *Proceedings of the ICST 3rd international conference on body area networks* (2008), 22.
3. Locher, I. and Tröster, G. Fundamental building blocks for circuits on textiles. *IEEE Transactions on Advanced Packaging*, 30 (2007), 837.
4. Schwartz, P. Structures and mechanics of textile fiber assemblies. Woodhead Publishing in Textiles, 2008.
5. Lim, H. Smart Underwear for Diabetic Patients. <http://ojs.cnr.ncsu.edu/index.php/JTATM/article/download/316/358>
6. McLellan, T.M. and Selkirk G.A. Heat stress while wearing long pants or shorts under firefighting protective clothing. *Ergonomics*, 4 (2004) 775–90.
7. Kovats, R.S. and Hajat, S. Heat stress and public health: a critical review. *Annual Reviews in Public Health*, 29 (2008) 41–55.
8. Chao, T.C., Sinniah, R. and Pakiam, J.E. Acute heat stroke deaths. *Pathology*, 13 (1981). 145–156.
9. Haymaker, W., Teabeaut, J.R., Krainer, R. and Schickele, E. Heat Stroke. *Journal of Neural Transmission*, 11 (1955) 142–145.
10. Givoni, B. and Goldman, R.F. Predicting rectal temperature response to work, environment, and clothing. *Journal of Applied Physiology*, 32 (1972) 812.
11. Kovacevic, S., Hajdarovic, K. and Grancaric, A.M. Influence on warp loading on weaving machines upon yarn deformation. *Textile Research Journal*, 70 (2000), 603.
12. Lederman, S.J. and Taylor, M.M. Fingertip force, surface geometry, and the perception of roughness by active touch. Reprinted from *Perception & Psychophysics*, 1972.
13. HAPTEX Deliverable D3.1 First set of measurements. http://haptex.miralab.unige.ch/public/deliverables/HAP_HAP-D3.1.pdf
14. Nunneley, S.A. Heat stress in protective clothing. *Scandinavian Journal of Work, Environment and Health*, 15 (1989), 52–57