Poster: One Leg at a Time: Towards Optimised Design Engineering of Textile Sensors in Trousers

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ABSTRACT

Custom made textile sensors encounter design and manufacturing challenges that differ from conventional printed circuit board-based sensors. The field of e-textiles commonly deploys such sensors on the human body, meaning that overcoming these challenges are crucial for reliable sensor performance. In this paper, we present and evaluate the design of trousers with embedded fabric sensors. Two iterative prototypes were manufactured and tested in two user studies, focusing on mechanical aspects of the design for applications in capturing body movement within social interaction. We report on failures and risks of the design, and furthermore propose solutions for a more robust, yet soft wearable sensing system.

CCS CONCEPTS

• **Hardware** → *Physical verification*; *Design rule checking*; • **Human-centered computing** → *Empirical studies in ubiquitous and mobile computing*.

KEYWORDS

E-Textiles ; Soft Circuitry ; Body Movement ; Body Centric Computing ; Sensor Design

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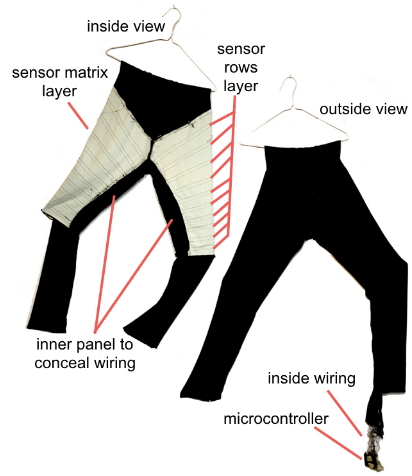

Figure 1: Front view of inner & outer layers of smart trousers, Prototype 1. Left: sensing area around thighs covered by blue fabric, shown inside out. Right: shell of trousers.

1 INTRODUCTION

What makes a good textile sensor? And, more specifically, what makes a good, wearable, textile sensor for an article of 'smart clothing'? In the field of wearable technology, pushing forward the state of the art for electronic textiles often relies on self-made sensors [7]. This particularly applies to applications in which data is collected from the body as it moves in spontaneous and unsupervised ways, such as in social encounters and with unconscious behaviours.

More conventional products using printed circuit boards bear the risk of being intrusive when collecting data. Knitted or woven fabrics consist of a material we are very familiar with which follows our movements more organically. As such they are particularly relevant to the wider field of ubiquitous and unobtrusive computing.

Handcrafted sensor designs can be evaluated against technical requirements like any other sensor system, but they are likely to have more sensor-to-sensor variability than sensors that can be purchased "off the shelf". There are several challenges that come with making your own textile sensors. One is the connection between flexible and rigid components which occurs when linking fabric sensors with electronics that textiles can not yet replace [2, 3]. This is a significant obstacle to the wider task of creating soft, wearable technology that is as physically robust as more rigid counterparts.

There is a great corpus of work assessing the performance, durability and washability [1, 6] of textile sensing systems. Depending on the intended application of a design, different test methodologies are followed. Usually, they can be divided into two approaches: lab-based tests and user studies. A systematic investigation of self-made sensors often happens on machines specifically built for these purposes [11], and can extensively test the sensors' behaviour over time and other material related characteristics. What is missing in this approach, however, is the potential deviation in performance in uncontrolled environments, the "real world". Other experiments address this aspect and further explore their e-textile sensors in more natural settings, such as directly on the human body during a specific task [8, 10]. While these aspects are all crucial in the process of developing a good sensor, it is important for these components not to be overlooked for a truly holistic assessment of a wearable sensor capturing bodily data: interactive settings in which body movement is not created in isolation in a lab environment, but within a more ecologically and natural context.

Measuring Body Movement with E-Textiles

Garments for wearable computing enable body movement to be captured in continuous, less intrusive ways than camera systems. By embedding soft sensor networks seamlessly in clothing and in direct contact with our skin, we can measure motion [5], and touch [12], amongst other things. Most commonly, upper body garments are used to collect this data, assuming that the torso, including the arms, is most relevant to identify these bodily signals. Recently, however, also the lower body has proven relevant, for example, with leg postures being decoded as behavioural cues [10] or for activity recognition [13]. Leg movement is distinct from torso movement and therefore accumulates different requirements to robustness of sensors. It encounters higher pressure, strain or abrasion in certain areas, through, for example, sitting down or walking. The development of smart garments for lower body data collection must account for these aspects.

In this paper, we address the challenges encountered when constructing a custom e-textile sensor system through a case study of smart trousers. They were originally designed for investigating postural behaviours in a seated conversational setting as further described in [10]. The trousers contain embedded handcrafted fabric pressure sensors developed to classify postural states from lower body movement. Here we present two user studies and further iterations of the sensors and trouser construction in order to propose solutions related to the design engineering of textile sensors for on-body applications.

2 A DESIGN WITH LEGS: PROTOTYPE 1

In the following section, we present the design and evaluation of our first prototype of 'smart' trousers with integrated textile pressure sensors. The focus of this work is the mechanical assessment of the textile sensors and their stability.

Prototype 1 Design

The number of sensors, their placement and the type of data to be collected were derived from ethnographic observations of seated multi-party interactions and is informed by identifying a variety of sitting postures commonly performed in social interaction. We provide a technical overview of the system, though a more detailed report on the design process can be found in [10].

Sensor Matrix. A matrix of pressure sensors were constructed for each leg of the trousers. The matrix consists of 10 rows and columns, creating 100 data points (or sensors) distributed around thighs and buttocks, see Figure 1. This design is adapted from Donneaud et al. [4].To be able to sense continuously around the thigh, the only sewn seam is along the inside of the leg (an inseam). The seam integrates a 5cm panel that encapsulates all wiring connecting the pressure matrix to the microcontroller at the ankle. A microcontroller (Teensy 3.2) was placed at the ankle of the trousers, hidden in the hem.

Materials. The pressure matrices were constructed from two types of fabric[1]: a highly conductive Zebra fabric (nylon yarn with conductive coating, see stripes in Figure 2), and a resistive stretch fabric, EeonTex LTT-SLPA[2]. The matrices were mounted on non-conductive jersey knit panels (pale blue fabric in Figure 1) that were then sewn into black jersey knit leggings-style trousers.

Wiring. Each stripe of the matrix, 10 rows and 10 columns, were connected to either a digital or analog pin on the microcontroller through insulated ribbon wire. At the end of each wire, the insulation was stripped and the wire was embroidered onto the conductive fabric. For the columns, these embroideries were placed just below the knee (Figure 2 top right), and the rows were linked to the circuit board (PCB) from the inner leg downwards (Figure 2 top left). All wiring was concealed from direct contact with the skin.

Prototype 1 Evaluation

Participants. A total of 26 participants, 17 female and 9 male, between 20 and 46 years, wore the first prototype of the trousers during three-way seated conversations.They were asked to put on the trousers by themselves, however were offered assistance.

[1]commercially available from distributor Hitek, https://www.hitek-ltd.co.uk
[2]Eeonyx, https://eeonyx.com

Procedure. After putting on the pair of trousers, the three participants sat down (around a table, on a non-spinning chair) and given a task to discuss and resolve amongst them. The interaction lasted 15 to 20 minutes, during which the pressure sensor data, as well as video was recorded and locally stored on an SD card (integrated in the circuit board on the trousers). At the end of the session, everyone was asked to stand up and to take off the trousers again.

Prototype 1 Results

By exposing the trousers to this quantity and type of use, we were able to evaluate not only the sensor performance, having recorded data of postural pressure changes, but also the mechanical and electrical hardware faults of the design.

Ripped Embroidered Wires. The most significant flaw of Prototype 1 was the lack of robustness in the hard-soft connections. Up to 4 wires were pulled out from the embroidered connection to the pressure matrix in a single wearing. With each wire connecting to a column or row of the matrix, that means 10 sensors failed to function with only one wire being disconnected. An inspection of the sensor data showed 4 participants with no faulty data, 12 with only one wire pulled, and 5 participants with either 2, 3 or 4 disconnected wires.

Prototype 1 Discussion

Participants reported feelings of restriction when putting the trousers on and moving their legs freely (e.g. leg crossing). The sensing area of the trousers consists of 4 layers in total, each layer of the sensor being attached to a separate piece of fabric, and being covered by the outer shell of the non conductive trouser legs. This did not limit movement as such, but can feel thicker than conventional trousers made of similar fabrics.

Additionally, while it was considered best for the design of the sensor matrix to have no side seam and only have a narrow panel along the inner leg to house the wiring, the tests showed that this position may increase the risk of the wires alongside the inner leg to be pulled of their embroidery.

Identifying such errors is useful for improving development in garment and sensor design. In the next section, we propose solutions to the encountered issues in order to produce a robustly functioning pair of trousers fit for 'real world' scenarios.

3 EVEN SMARTER TROUSERS: PROTOTYPE 2

Through the results of the evaluation of Prototype 1, we were able to develop and implement design related improvements towards a more robust, comfortable pair of sensing trousers.

Figure 2: Wiring for smart trousers. Top to bottom: embroidered insulated wires (Prototype 1); sewn conductive yarn insulated with paracord (Prototype 2); conductive yarn insulated with tubular weft knit techniques (future iteration).

Prototype 2 Design

Significant changes of this iteration of the trousers concern the connections between textile and electronic components, as well as the overall wearing comfort. To improve this, the pattern construction was slightly adapted through adding a side seam, the fabric layers were reduced, and instead of metal wires, conductive threads were embedded.

Hard-Soft Connections: Textile Wires. Instead of using ribbon wire, conductive copper yarn[3] was insulated with textile paracord, following the techniques in [9]. Using yarn instead of wire has the advantage of being more soft, flexible, and being sewable with a conventional domestic sewing machine. In Prototype 1, a total of 20 wires were all running along the inner leg down to the ankle. This added to bulkiness of the design. In Prototype 2, the less bulky fabric wires were distributed to run alongside the inner and outer side of the leg. The 'wires' for the matrix columns ran along the inside leg, with the rows running along the outer side seam.

Reducing Layers. Following comments from the first set of participants regarding the uncomfortable thickness of the trousers around the sensing area, the layers for the second iteration were reduced by half. This was achieved by using thermal bonding to attach the conductive fabric stripes forming the sensor matrix directly onto the non-conductive fabric, seen in Figure 2 (middle). While in Prototype 1, the stripes were stitched on a separate piece of jersey knit to enable easier detachment and independent manufacturing processes, we could overcome these precautionary measures without restricting the sensing performance.

Prototype 2 Evaluation

Participants. 10 participants, 8 female and 2 male, tested the new trousers. All the participants (with the exception of 1

[3]Purchased from Karl Grimm, http://www.karl-grimm.com/

male) took part in the first evaluation and were between 25 and 36 years.

Procedure. The setting for the evaluation was a single user study. Participants put on the trousers by themselves and were asked to perform a series of sitting postures that were identified in the previous data set. In particular, the postures performed were : sitting down; crossing both legs; leaning forward with elbows on thighs; rubbing thighs with hands; hands resting on knees; bending and stretching lower legs; and fidgeting.The sequence of postures were performed twice by the participant before being asked to take off the trousers again. After each session, the trousers were inspected for any errors or broken elements, with special attention given to the new yarn based wiring. Participants were also asked to comment on the comfort and wearability of the trousers.

Prototype 2 Results

None of the yarn-based 'wires' were ripped from the pressure matrices. All participants mentioned improved comfort and reduced thickness of the trousers. Six participants pointed out an overall 'softer' touch of the trousers. It was also reported that movement could be performed more comfortably and without concern for damaging the sensors in the trousers.

4 DISCUSSION: NOT ON THE LAST LEG

When comparing the number of wires damaged, ripped or pulled, Prototype 2 clearly outperforms the first trousers, with no damage being done to the wire connections. Sewing conductive thread instead of embroidering wires probably contributed the greatest improvement to the design and also allowed for more flexibility in the placement of the yarn-based 'wires'. This means they can be placed in areas that are less subject to higher pressure, strain or abrasion.

This evaluation focuses on the mechanical aspects of the design engineering, which is only one factor to consider for smart garments. Nevertheless, it provides useful guidelines for designing wearable technology systems for body-centric sensing that work reliably not only in a controlled, lab based environment, but also in more ecologically valid settings.

We close by proposing a third prototype building on the findings from the evaluation of the first two. As securely routing the electrical connections with less bulk improves wearability and robustness of the trousers, the electrical 'wires' can be integrated directly into the fabric of the garment to further improve performance. The bottom of Figure 2 shows a swatch of a knitted fabric seamlessly creating insulating tubes which can hold conductive yarn. By knitting tubular elements into the fabric, the copper yarn is insulated without further post-manufacturing processes, as used in the earlier prototypes described here.

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REFERENCES

[1] Mary Ellen Berglund, James Coughlin, Guido Gioberto, and Lucy E Dunne. 2014. Washability of e-textile stretch sensors and sensor insulation. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers - ISWC '14*. ACM Press, New York, USA, 127–128. https://doi.org/10.1145/2634317.2634326

[2] Leah Buechley and Michael Eisenberg. 2009. Fabric PCBs, electronic sequins, and socket buttons: Techniques for e-textile craft. *Personal and Ubiquitous Computing* 13, 2 (2009), 133–150. https://doi.org/10.1007/s00779-007-0181-0

[3] Leah Buechley and Hannah Perner-Wilson. 2012. Crafting technology: Reimagining the processes, materials, and cultures of electronics. *ACM Transactions on Computer-Human Interaction (TOCHI)* 19, 3 (2012), 21.

[4] Maurin Donneaud and Paul Strohmeier. 2017. Designing a Multi-Touch eTextile for Music Performances. In *Proceedings of the 17th International Conference on New Interfaces for Musical Expression (NIMEâĂŹ17)*. Aalborg, Denmark, 15–19.

[5] Richard J.N. Helmer, Michael A. Mestrovic, Damian Farrow, Stuart Lucas, and Wayne Spratford. 2008. Smart Textiles: Position and Motion Sensing for Sport, Entertainment and Rehabilitation. *Advances in Science and Technology* 60 (2008), 144–153. https://doi.org/10.4028/www.scientific.net/AST.60.144

[6] Md. Tahmidul Islam Molla, Crystal Compton, and Lucy E. Dunne. 2018. Launderability of surface-insulated cut and sew E-textiles. In *ISWC '18 Proceedings of the IEEE International Symposium on Wearable Computers*. ACM, 104–111. https://doi.org/10.1145/3267242.3267255

[7] Hannah Perner-Wilson and Leah Buechley. 2010. Making textile sensors from scratch. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*. ACM, 349–352.

[8] Francisco Pizarro, Piero Villavicencio, Daniel Yunge, Mauricio Rodríguez, Gabriel Hermosilla, and Ariel Leiva. 2018. Easy-to-build textile pressure sensor. *Sensors (Switzerland)* 18, 4 (4 2018). https://doi.org/10.3390/s18041190

[9] Irene Posch and Geraldine Fitzpatrick. 2018. Integrating Textile Materials with Electronic Making. Association for Computing Machinery (ACM), New York, New York, USA, 158–165. https://doi.org/10.1145/3173225.3173255

[10] Sophie Skach, Rebecca Stewart, and Patrick G T Healey. 2018. Smart Arse: Posture Classification with Textile Sensors in Trousers. *Proceedings of the 20th ACM International Conference on Multimodal Interaction* (2018), 116–124. https://doi.org/10.1145/3242969.3242977

[11] Rebecca Stewart and Sophie Skach. 2017. Initial Investigations into Characterizing DIY E-Textile Stretch Sensors. In *Proceedings of the 4th International Conference on Movement Computing - MOCO '17*, Vol. Part F1291. 1–4. https://doi.org/10.1145/3077981.3078043

[12] Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbaek. 2018. zPatch: Hybrid Resistive/Capacitive eTextile Input. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, Stockholm, Sweden. https://doi.org/10.1145/3173225.3173242

[13] K. Van Laerhoven and O. Cakmakci. 2002. What shall we teach our pants?. In *Digest of Papers. Fourth International Symposium on Wearable Computers*. 77–83. https://doi.org/10.1109/iswc.2000.888468