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Design and characterization of a textile extension sensor for sports and health applications

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Abstract. Electronic textiles (e-textiles) are a form of textiles that, integrating technology, can add new functionalities or forms of expression. The fabric can, for instance, have sensing properties, emerging as a textile sensor, which is a subfield of the e-textiles, widely reported in literature. One such kind of sensors are the extension sensors, usually studied for breathing monitoring, posture detection or characterization of movements. There are several challenges associated with the production of a textile extension sensor with high precision and repeatability. This paper reports the design and development of a knit-based sensor that uses a thermoplastic polyurethane (TPU) adhesive and film to either bond or insulate the sensing area (respectively), in order to improve the sensor's performance. The sensors were found to be appropriate for measuring breathing rate, but not for absolute extension measurements. The use of elastic tape or TPU produced the most stable results.

1. Introduction

There has been an increased interest in exploring e-textiles to build sensors that are able to read physiological and biometrical data in real-time, with more products appearing on the market. What seems to be the most appealing characteristic of this kind of sensors is the fact that we are in constant contact with textiles, almost as if they are an intrinsic part of our bodies.

Wearable sensors may play a fundamental part making instruments for healthcare widely available, allowing better healthcare management. They are expected to allow continuous monitoring of the person, in real time. But they can also be of significant value in sports, leisure or daily activities.

Textile-based strain sensors are an example of the many textile based sensors that have been studied and reported in literature, mostly focusing on the monitoring of breathing rate or posture, and characterization of movements. Most textile-based stretch sensors reported in literature are based on the piezoresistive effect – changes in electrical resistance due to deformations of the material – however, other properties can also vary when stretching a material, and have been reported.

Gioberto and Dunne [1] have studied the possibility of using a four-thread overlock stitch, in which a conductive yarn forms the upper looper thread, as a stretch sensor. They have found that, when the fabric stretches to a certain dimension, the contact points between the loops decrease, resulting in an increase of the electrical resistance, but after some point, the conductivity slightly increases again. In another study [2], the authors have explored the properties of a two-needle coverstitch with top and bottom cover, in which the top thread is replaced by a conductive yarn (silver coated polyamide). The sensor is fairly linear in the extension range in which it is used and, although it produces a small resistance variation (approximately 9 ohms), it is enough to detect breathing rate.

Ramos-Garcia et al. [3] has used a coverstitch to create a sensor to monitor breathing rate. He has also used a bonding tape to insulate the sensor. Tests were carried out and the measurements were compared to a commercially available belt (SleepSense Inductive Plethysmography). Although the sensor has shown some potential, its precision still needs to be improved, with the breathing rate error increasing in each cycle.

Stewart and Skach [4] have compared three conductive knitted fabrics as potential candidates for strain sensors. The authors have produced two of the sensors, one in a flatbed knitting machine and the other by hand knitting, with a stainless steel coated polyester yarn. The third substrate was a commercially available conductive knitting fabric (silver coated polyamide/elastane fabric, by Eeonyx), produced in a circular knitting machine. The tests showed that the difference between the first two knitted fabrics, in terms of signal acquisition, is not significant, with these two fabrics presenting low stability and producing much noise, unlike the latter, which seems to be a better candidate for strain measurement.

Atalay et al. [5] studied the effect of knitting structure compactness on electrical resistance and sensing characteristics. Three knitted strain sensors were compared. The samples were produced in a flat-bed machine, differing in either the elastomeric yarn input tension (thus varying the structure density) or elastomeric yarn thickness – one sample varies in yarn tension and the other differs in yarn thickness, both in relation to the first sample. The conductive yarn (silver coated polyamide) was embedded in a cotton interlock knitted structure. Tests were done to determine the change in resistance as a function of fabrics extension. The authors found that the sample with the thicker elastomeric yarn, which is also the most compact structure, is almost linear in all its extension, while the other sensors have a smaller linear region.

Zhang [6] has compared jersey-based knitted structures (single jersey, combination of jersey and float loops, and combination of jersey and tuck loops) as possible candidates for strain sensing. The samples were all produced in seamless knitting machine. The sensing yarn is a stainless steel polyester coated yarn (Bekaert Bekintex). The tests indicated that the sensors would become more stable after 50% elongation, thus suggesting that a pre-tension would allow the sensor to work in a more linear region. Also, the single jersey fabric seems to produce more stable results. The author also ran some tests, coating the samples with silicone, to understand the effect of a silicone layer on the sensor's performance, but it didn't improve the sensor's response, as initially expected.

Not all textile sensors are based on the piezoresistive effect. Guay [7] has introduced a spiral antenna in the chest of a t-shirt, to monitor breathing rate. The spiral antenna is composed of silver coated polyamide/glass fibre. The expansion of the chest stretches the antenna, varying its resonant frequency, which is proportional to the breathing rate. Krehel et al. [8] has used optical fiber to create a sensor that detects changes in light intensity as a response to strain, to monitor breathing rate. An LED emits light into one side of the optical fiber, while a photodiode detects the remaining light that reaches the other end of the fiber.

Disregarding the method, producing a sensor with high precision seems to be a great challenge when using e-textiles. This paper reports the study of knit-based extension sensors. Knitted extension sensors have been widely reported in the literature, but in this project, thermoplastic polyurethane (TPU) adhesive and film, which is claimed to have a good elastic recovery, were used, either to bond the conductive knit fabric to a non-conductive substrate or to create a protective layer. This material should improve the elastic recovery, thus providing a better signal response.

2. Materials and Methods

Three samples of extension sensors were produced and tested (figure 1). In all samples, conductive knitted strips were cut in the weft direction and bonded to a textile substrate, using a polyurethane based thermoplastic adhesive (Bemis 5256), which improves elastic recovery. The conductive knitted fabric is a jersey fabric composed of cotton (83%) and silver coated polyamide (17%) – Statex Silverell. The strips are of 13 cm length and 1 cm width. They are bonded to a knit fabric strip of 20 cm length. In samples 1 and 2, the sensors are bonded to a jersey PA/EL fabric and in sample 3, it is bonded to an elastic band. In sample 2, the strip was covered with a TPU film (Bemis Exoflex 3900) that slightly decreases elasticity, while improving the fabric recovery. The strips and TPU film were bonded to the substrates using a flat press machine, at 130º and 5.5 Bar, for 20s.

Figure 1. Sensor samples: 1- conductive knit thermobonded to a jersey fabric; 2- equal to sample 1, but reinforced with a TPU layer; 3- conductive knit thermobonded to an elastic band.

Preliminary tests were executed to determine the change in voltage over time. A dynamometer was used to stretch the textile sensor, during 10 cycles, and obtain the variation of force in relation to elongation. A Fluke 45 multimeter connected to a PC was used to measure the electrical resistance during stretching and relaxing. The multimeter only allows a sample rate of two samples per second, which is not enough, especially for trials with higher extension speed. For this reason, a signal conditioning circuit was built to produce a voltage according to the extension and thus electrical resistance of the sensor. The signal conditioning circuit is connected to a National Instruments NI-6210 data acquisition board and sampled at 1000 Hz.

Knowing the voltage in response to extension, it is also possible to determine the electrical resistance variation. The relation between sensor resistance and output voltage, as reported in [9], is given by

$$Vo = Voff\left(1 + \frac{R}{Rs}\right)$$

where V_o is the output voltage, V_{off} is the offset voltage, R is the feedback resistance and Rs is the sensor's resistance. As can be seen, the output voltage is reciprocal to the resistance. Previous experiments have shown, however, that resistance variations varies similarly with extension. The circuit's transfer function thus provides some linearization of the voltage versus extension function.

The elongation versus force data are obtained from the dynamometer. Then, for each trial, two data sets are combined: voltage over time, and elongation versus force at a constant speed. The combination provides voltage versus elongation.

The various tests were executed with different values of speed, elongation and pre-tension. Three trials are reported: test A starts with the samples relaxed and stretches 48 mm, at a speed of 200 mm/min; B and C were done with a small pre-tension (20 mm) and the samples were stretched 18 mm, at 200 mm/min and 400 mm/min, respectively (the latter was done to simulate breathing). Adding some pre-tension is expected to set the resistance and voltage behavior in a more linear region [6]. Moreover, it would be more similar to a slim fitted shirt.

3. Results and Discussion

3.1. Trial A

The variation of resistance and voltage over time is represented in Figure 2 (note that resistance and voltage cannot be measured during the same test, they are obtained in separate runs). As expected, resistance varies reciprocally to extension (Figure 2 a), and it can be observed that the voltage waveforms vary almost linearly with extension (Figure 2 b), as previously discussed.

Samples 2 and 3 are the one showing the most stable maximum voltage levels (corresponding to the lowest resistance values, i.e. the highest elongations). Sample 1, not stabilized by a TPU tape or the elastic band, shows a more variable behavior. At minimum extension, all sensors present some instability, despite the stabilization through the TPU or elastic band, but it is worse with sample 1.

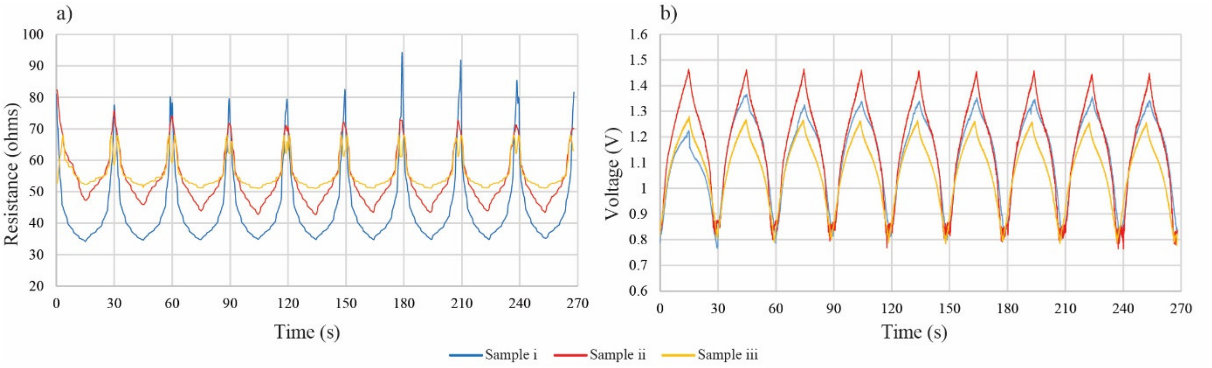

Figure 2. Resistance and voltage over time, for the three samples (two separate tests for resistance and voltage)

In Figure 3, voltage output is plotted against elongation of the sensor. It can be seen that after some elongation value, different from sample to sample, the relation becomes almost linear. Overall, the behavior of the sensors is more stable with the samples using TPU or set on elastic tape.

With increasing elongation, the variations become smaller, as if the sensor is saturating. This is particularly noted for sample 1 and 3.

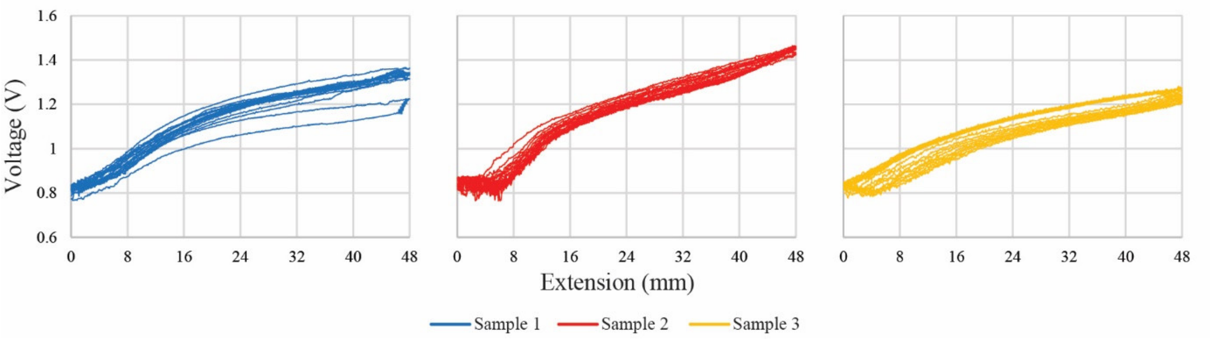

Figure 3. Variation of voltage versus elongation

3.2. *Trials B and C*

Figure 4 shows the results of trials B and C (for simplicity, only the voltage output is represented). In both graphs, sample 3 shows the lowest voltage offset and amplitude. Sample 2 has the highest voltage, as in previous results. However, from one trial to the other, both voltage offsets and amplitudes vary significantly. Sample 2 produces an increase of amplitude from B to C, whilst sample 1 shows a decrease.

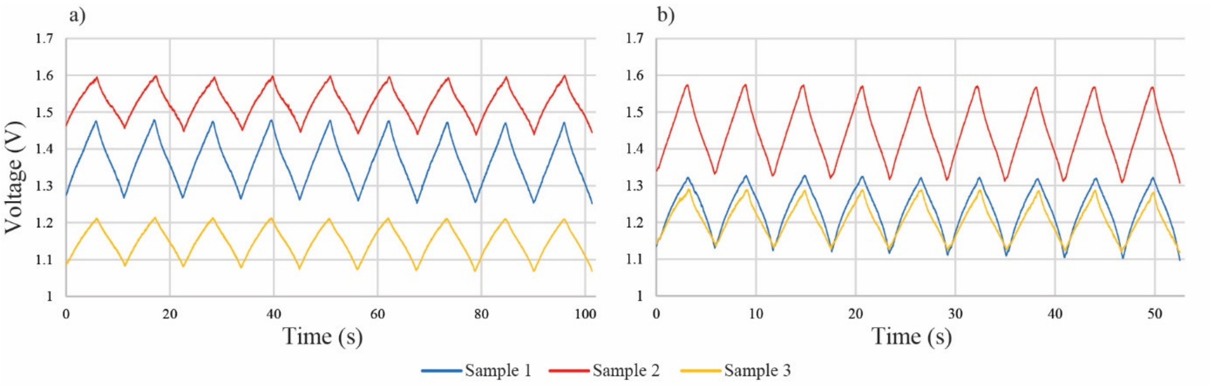

Figure 4. Voltage variation over time: a) trial B; b) trial C

It can thus be observed that the signals have different offsets and amplitudes from one trial to the other, although the extension they are subjected to are the same. Only sample 3 presents approximately the same amplitude at the two speeds, but varies in offset. Besides that, the voltage signal varies almost linearly with elongation for all samples.

The fact that offset and amplitudes of the signals are unstable from one trial to another means that these sensors are not appropriate to make absolute measurements of extension or force. However, the signal is clean and constant regarding the calculation of the movement frequency.

Figure 5 presents the voltage versus elongation graphs, once again confirming the almost linear behavior, some hysteresis and variability between cycles, and varying offsets and amplitudes.

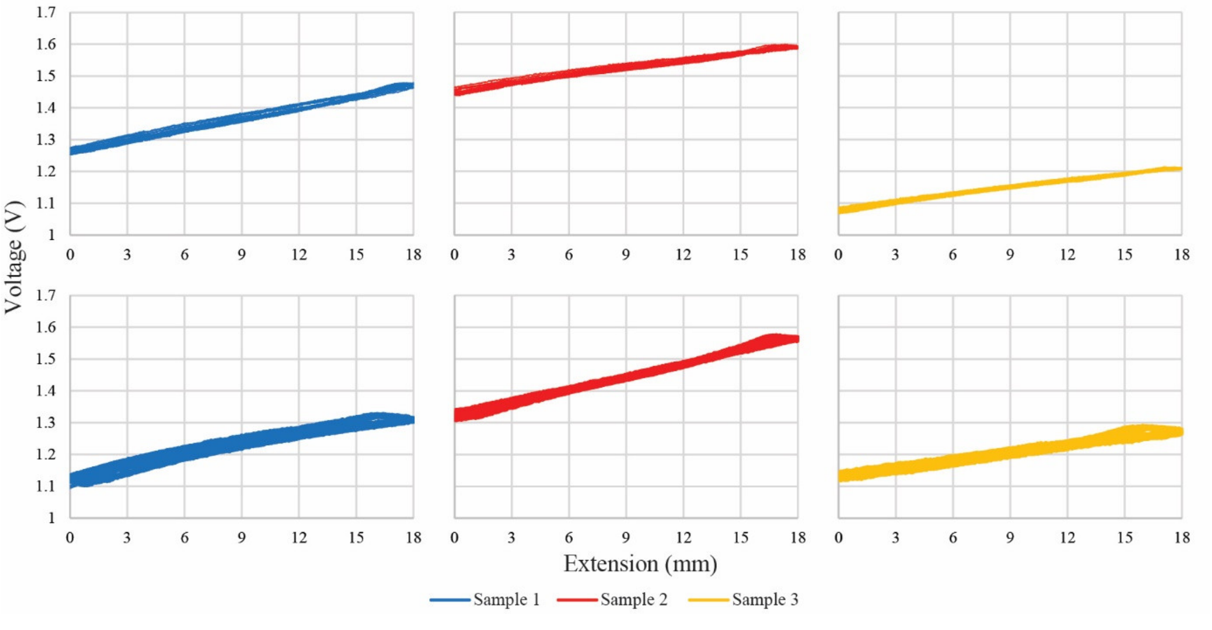

Figure 5. Voltage variation in response to elongation – trials B (top) and C (bottom)

4. Conclusion

Knit-based extension sensors, using thermo bonding materials (TPU film and adhesive) to bond the sensing material (conductive knit fabric) to a knitting substrate, were produced and tested. Three samples were produced and the results were reported.

All three samples show some potential for breathing rate monitoring, considering that the variation rate is clearly depicted by the voltage signals produced. For parameters where an absolute measurement is required, such as posture or joint angles, higher precision is required.

The adhesive used to bond the conductive knit fabric to another textile substrate seems to have a positive effect on the sensor's behavior. Having it bonded to an elastic band, which has a higher elastic recovery, or applying a TPU layer over the sensor also seem to produce better results.

Another positive factor is the existence of a pre-tension that allows the sensor to work in a region where an almost linear voltage output is obtained.

Changing the speed of the dynamometer (from 200mm/min to 400mm/min) shouldn't have resulted in the shift in offset voltage and amplitude that can be observed in figure 4. Ideally, the sample should have had the same behavior at different speeds. The trials shall be repeated in the future, to check if it is consistent with these results.

Future trials shall include repeating some of the previous tests to check for consistence, producing more samples and test them to check the repeatability of this production method. Furthermore, washing tests will be run to understand the sensor's behaviour with washing.

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