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INTEGRATION AND EMBEDDING OF VITAL SIGNS SENSORS AND OTHER DEVICES INTO TEXTILES

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The development of ubiquitous vital sign monitoring has become a very up-to-date research theme for many academics and industrial companies in the last years. With new materials and integration techniques, it is possible to implement vital sign monitoring in an economic manner, directly into textile products. This unobtrusive presence of sensors is especially important for the monitoring of children or elderly people. This paper focuses on two aspects of sensor integration: Integration of off-the-shelf electronic components, and the use of the textile material itself as sensor, or in general as an electrically active element presenting some exploratory work in the integration of electronic devices into textiles. The main objective was to reproduce and improve on previous work presented by other authors, and foster possibilities of developing garments for vital sign monitoring with immediate industrial and economic feasibility. The use of standard production techniques to produce textile-based sensors, easily integrated into garments and with mass-market potential, is one of the important motivations for this work.

INTRODUCTION

Regarding the integration of electronics into textiles, it is possible to consider various levels of integration.

In a first level, commercially available electronic components are integrated into garments using special design elements fitted to the textile product exclusively to allow the introduction of the external component(s).

In the next level, the textile material itself is used as an electrically active component. Its function is provided by the properties of the base material, by structural properties or by introducing electrically active textile elements by embroidery.

A further step would be to implement electronic circuits within the fibres themselves, but at the time being technology is still far from providing tools to achieve this intent.

The growing availability of flexible and miniaturised sensors and electronic components has made the first level of integration quite straightforward. Regarding the embedding of the sensors into the textiles, more advanced techniques are required. A first step is to implement the sensors using textile materials based on conducting yarns or yarns with sensing properties (piezoelectric, optical fibres). Still, all the signal treatment has to be done outside the textile, by means of a dedicated electronic device.

The authors of this paper have conducted some exploratory experiments with several techniques intending to achieve measurement of heart beat and respiratory rate, using both inexpensive off-the shelf sensors and piezoelectric polymer sheets, as well as fabrics knitted with conducting yarns, acting as sensors.

A review of the state-of-the-art, an overview of general principles and the results obtained in the experiments will be given.

REVIEW OF THE STATE OF THE ART

Several efforts to create prototypes of wearable functional devices have been made in the last years. Most of them consider the approach of joining conventional off-the-shelf electronic devices to fabrics, such as microcontrollers, LED´s, optical fibres and all kinds of sensors, especially electrodes for ECG measurement.

The consolidated textile technology for integrating conductive yarns into knitted or woven fabrics and the implementation of sensors through embroidery has encouraged their use as suitable means for connection, data communication and power transfer.

The following paragraphs will outline contributions to the e-textile field which were developed by several research groups in the last few years, taking into account the performance of the devices.

In the 1990s, Lind *et al* from the Georgia Institute of Technology in Atlanta/USA developed a so-called *Smartshirt* [1], where off-the shelf sensors could be reversibly attached for monitoring several vital signs. Later on, the same authors developed an instrumented uniform called *Sensate Liner* which consists on a form fitting garment containing and interconnecting textile sensing elements to an electronic pack equipped with a processor and a transmitter. This uniform was developed for monitoring the medical condition of military personnel.

A baby pyjama with integrated sensors [3] is conceived as a prevention tool for the sudden infant death syndrome, operating an alarm in case of potential danger. The babysuit uses textile ECG electrodes and a respiration sensor both knitted from stainless steel yarn.

Ottenbacher *et al* (University of Karlsruhe) [4] integrated an ECG system with *Bluetooth* communication into a T-Shirt. Some of the components are incorporated into the garment, while the flexible electronic system is removable so that the garment can be washed.

ETH of Zurich/Switzerland developed e-textiles for functional electrical stimulation, embedding electrodes by using embroidery techniques for the integration into a textile substrate of conducting yarns, made of silver coated fibers [5].

Paradiso *et al* (University of Pisa) and Smartex in Italy developed a system named *WEALTHY*, where conducting and piezoresistive materials in form of fibres and yarns are integrated in a garment and used as sensor and electrode elements to assist cardiac patients during rehabilitation or professional workers that are under considerable physical and psychological stress [6].

Many more authors have provided important contributions to this area. The selection here presented reflects the most important work in the context of the current paper.

OVERVIEW OF GENERAL PRINCIPLES

A definition for e-textiles (electronic textiles) could be a multifunctional wearable human interface, capable of making daily life healthier, safer and more comfortable, integrating sensing or stimulation properties, capable of transmitting and processing data.

As previously described, to develop such an interface, there are two possibilities: Using commercially available sensors adequate for integration into textiles, or implementing the sensors using textile materials. The commercial sensor used in this work is piezoelectric film, sensors that are based on a polymer that exhibits the piezoelectric effect. In piezoelectric materials, a voltage appears as a consequence of mechanical stress. This effect is reversible, i.e, a piezoelectric material will produce a mechanical action when excited by an electrical potential. The use of polymers printed on flexible sheets allows the production of extremely flexible and sensitive sensors that can be integrated into textiles with relative ease.

Considering that any electrical conductor varies its resistance according to temperature and also according to strain, it is theoretically possible to use this effect for sensing purposes by integrating electrically conductive yarns into textiles. The general principle of the textile sensors tested in this work is based on the variation of electrical resistance with strain. This can be achieved by applying the stress directly to the yarn. It is also known that fabrics knitted with conducting yarns vary their overall electrical resistance depending in the extension they are subject to, thus behaving as extension sensors [3][7][8]. Another way of producing textile sensors is through embroidery, using conductive threads [9]. Several possibilities of inductive, capacitive or resistive sensors (sensors varying inductance, capacitance or resistance with geometrical, physical influences or chemical influences) exist, but were not explored in this work.

EXPERIMENTAL DETAILS, RESULTS AND DISCUSSION

Respiratory rate and heart beat frequency with piezoelectric film integrated into textile

The device was based on a DT-Series piezo film with lead attachments, from Measurement Specialties Inc (Figure 1 left). The sensor was integrated into an accessory that is clipped onto a strap with standard garment clips. The electrical connection of the sensor is embroidered onto the textile substrate receiving the sensor, and a female garment clip is applied onto the embroidered contact to serve as an electrical connector. The cable receives the male part of the clip (Figure 1 right).

Piezoelectric film sensor

Measurement accessory

Figure 1. Piezoelectric sensor integrated on textile.

The piezoelectric sensor is then connected to a charge amplifier[1] designed to assure an appropriate low-frequency response to accurately display the relatively slow breathing movement. A simple Labview program was developed to display the signal in a PC equipped with a data acquisition board.

As expected, the piezoelectric sensor revealed extremely sensitive and does not cause any discomfort due to its flexibility. The breathing movement is clearly depicted (Figure 2).

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[1] A charge amplifier is an electronic circuit specifically used for the conditioning of signals from piezoelectric sensors.

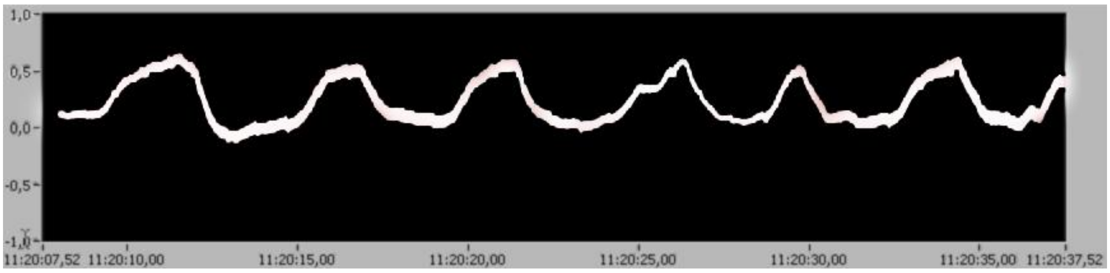

Figure 2. Breathing signal acquired by piezoelectric film sensor (x-scale: Time, y-scale: Volt).

Superimposed on the breathing signal it is possible to observe the heart beat signal, although this component only becomes evident when the wearer holds his breath (Figure 3). It is possible to extract the heart beat frequency by using spectral analysis techniques. Unfortunately, the sensitivity of the sensor is also a disadvantage, considering that any movement by the wearer may blur the remaining signals for analysis. A low-pass filter at about 1Hz could solve this problem, but it would also filter out the heart beat component, leaving only the breathing signal. Simple movement detection is extremely efficient with this sensor, and in this case the assembly could be redesigned for more wearing comfort.

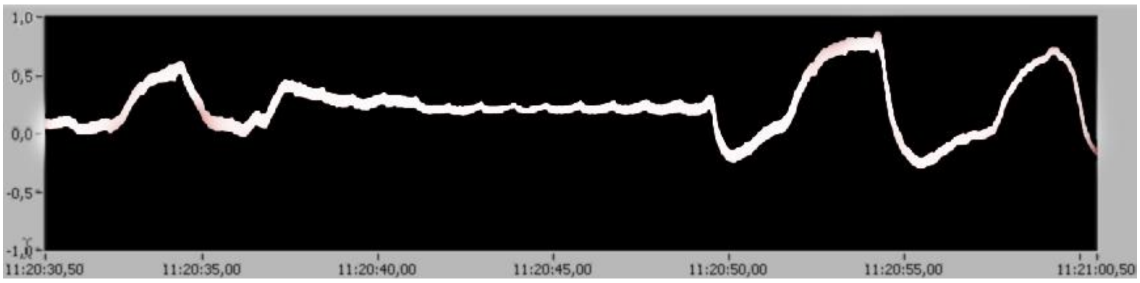

Figure 3. Heart beat signal acquired by piezoelectric film sensor (x-scale: Time, y-scale: Volt).

Respiratory rate: Textiles used as extension sensor

Following up on the work that used knitted fabrics as extension sensors to measure breathing rate [3][8][8], some samples were knitted in three different structures, using a yarn that is a blend of polyester and stainless steel in a proportion of 80/20 % (Bekaert Bekinox$^{®}$ Nm 50) and has a perfectly “textile” touch comparing to a pure stainless steel yarn. The first experiments showed that the sensors had limited performance. The main problems presented by this sensor are its high non-linearity and hysteresis, and an evident instability of the electrical resistance values measured, producing a fluctuation of the signals.

Still, it was possible to develop a measurement accessory (Figure 4) and obtain interesting signals, as shown in Figure 5.[2]

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[2] The signal conditioning was in this case achieved by an operational amplifier in an inverting configuration and using the sensor as feedback resistance, thus amplifying a reference voltage in proportion to its electrical resistance.

Figure 4. Accessory using knitted fabric as extension sensor.

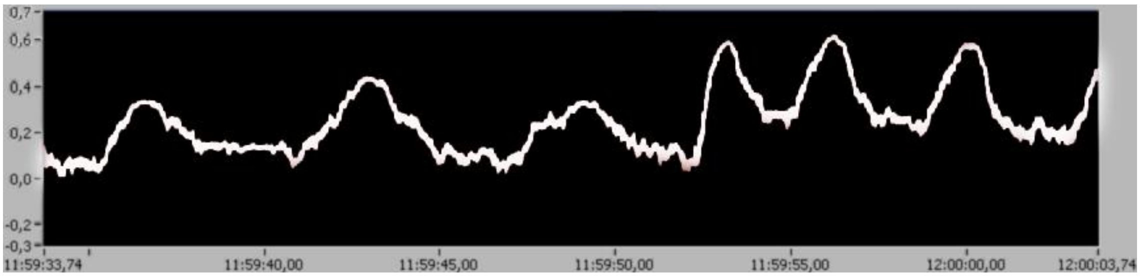

Figure 5. Breathing signal acquired by knitted sensor (x-scale: Time, y-scale: Volt).

To improve the sensor’s behaviour, new sensors were produced and tested with more detail.

A rib 1x1 structure based on the Bekinox yarn and plated with Spandex® was produced. Spandex® was used in order to improve the capability of the fabric to completely recover the initial physical characteristics and hopefully the electrical properties. The samples were inserted into a Houndsfield dynamometer with the intent to exactly control the extension applied to it and observe the behaviour of the electrical resistance when subjected to consecutive ascending and descending excursions of extension.

The experiment showed that the rib fabric has a nonlinear behaviour with respect to electrical resistance variability, with severe differences in resistance between ascending and descending excursions, particularly for low extensions. For higher extensions the resistance has a small non linearity (Figure 6, right). Between 60 and 72 mm, the electrical resistance presents a quasi linear behaviour.

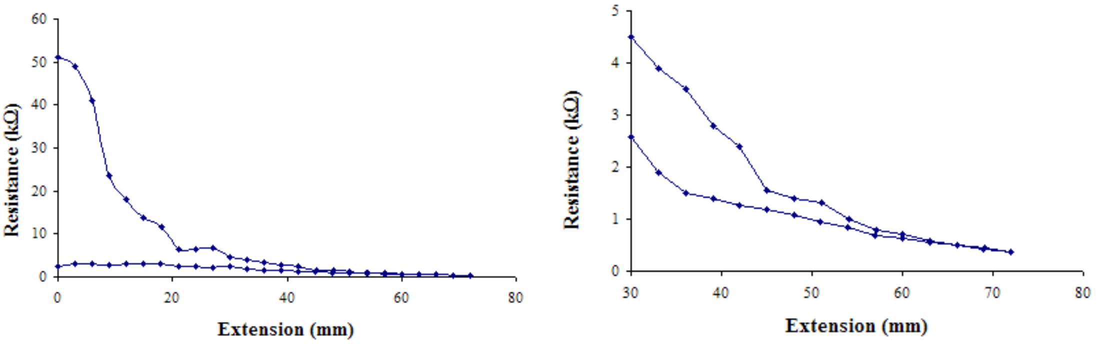

Figure 6. Electrical resistance variability for Rib 1x1 with Spandex® (sample of 10cm length x 4 cm width).

The other structure was Jersey, again plated with Spandex®. Figure 7 illustrates the resistance curve for this structure when the axial tensile force is applied in the wale direction. With this configuration the resistance is quite high and measured in MΩ. The general behaviour is quite similar as for rib since the resistance falls down as the extension increases. However, there is a significant decrease in resistance for higher extensions, namely on the 20-25 mm range. It is also possible to observe that from 12 mm up to 25 mm one can find a relatively well behaved resistance curve.

The plausible explanation for the relatively high resistance can be found in the structure of jersey. There is not a natural path for the current to flow as it happens when the resistance is measured in the course direction. The current flows throughout each contact between a loop located of the previous course and a loop of the course immediately located above (or below). This results in a small metallic contact surface, thus resulting in a higher resistance. On the contrary, the electrical conductivity of jersey fabric when measured in a course direction is quite increased since the yarn is part of each loop of that course. As a consequence, the resistance dramatically decreases.

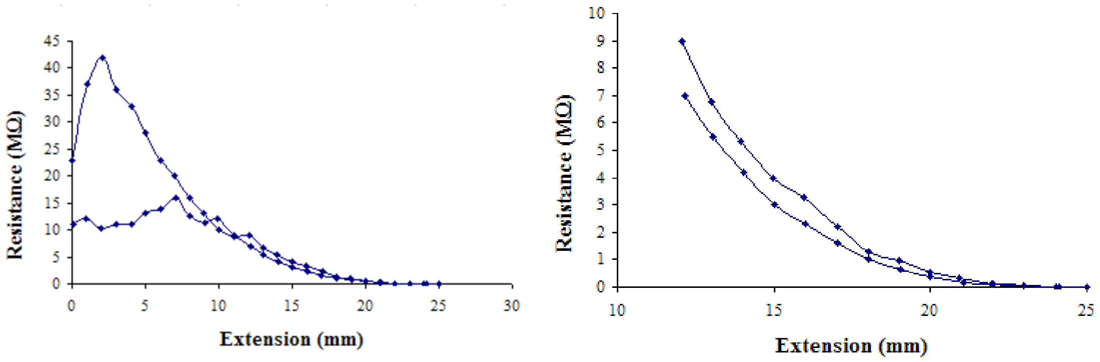

Figure 7. Electrical variability for jersey fabric. Sample of 4cms length x 5 cms width.

Nevertheless, it was not possible to obtain a significant improvement in this second experiment with knitted sensors. Important characteristics such as linearity, hysteresis, repeatability and the sheer stability of the measured values are not fully satisfying. Further attempts are planned, using different dimensions for the sensors, and inserting Spandex® into the fabric in different ways.

An interesting idea is to use the yarn itself as the extension sensor, possibly inserted into a plain weave. To investigate on this approach, some measurements were made on yarn samples.

Before performing the experiments, the stress-strain curve for this yarn was obtained using standard ISO 2062 and the elastic zone identified. The yarn was then submitted to axial traction up to the maximum extension where the elastic zone is available and in predetermined extensions the electrical resistance was measured.

As Figure 8 illustrates, the yarn presents a hysteretic behaviour, with the electrical resistance decreasing as long as the yarn is extended, starting from 1.25 kΩ for 0 mm up to 0.90 kΩ for 15 mm. The resistance variability has a nonlinear behaviour, but unlike the knitted samples, the resistance values measured are quite stable. A careful observation of this figure suggests that there might be an extension interval, from 5 to 10 mm, where the yarn can be considered as having a linear behaviour. In fact, the regression lines are quite similar for that region.

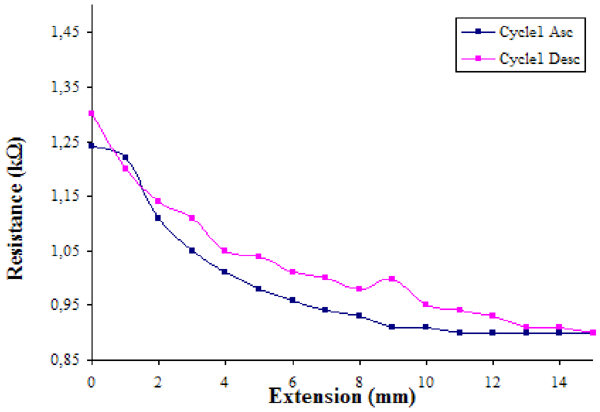

Figure 8. Electrical resistance versus extension for conductive yarn. Sample length 50 cms.

When subjecting the same sample to consecutive excursions, one can observe the general nonlinear behaviour (Figure 9). However, it is evident that stretching and afterwards releasing the yarn results in a significant increase of the resistance, in particular for low extensions. The descending excursions reveal a marked nonlinearity.

On the other hand, the ascending excursions indicate that the nonlinearity is not so evident. From the observations made, it seems clear that a predefined tensile force should be used and thus the yarn stretched only from a predefined extension up to the highest extension. This procedure would probably allow repeatability for the electrical resistance.

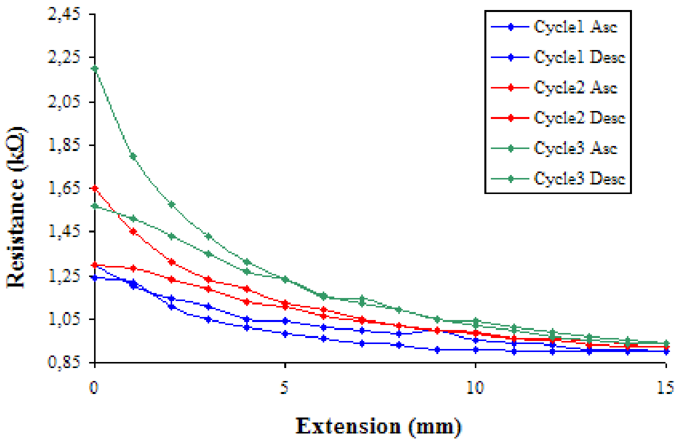

Figure 9. Consecutive excursions on the same conductive yarn.

CONCLUSIONS

The possibility of using more or less conventional textile materials to implement sensing functions is feasible, but the performance of the proposed devices is quite limited. It seems that the sensors are able to provide repeatability only on segments of the measuring range. Both the structure of the yarn as well as the knitted structure of the fabric are quite complex. The contacts between the conducting fibres in these arrangements determine the electrical resistance of the sensor. However, in consecutive extensions the arrangement of the yarns and conducting fibres is always slightly different, thus negatively influencing repeatability. Further optimisation may be achieved in future work, but it will be difficult for these devices to fulfil full medical requirements, especially considering the day-to-day use and care they are subject to. More advanced materials, using piezoresistive and piezoelectric coatings on a filament level, and inserted into fabrics through weaving or embroidery, are more likely to achieve the desired accuracy.

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