Textile Strain Sensors Characterization

- Sensitivity, Linearity, Stability and Hysteresis

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ABSTRACT In this paper 4 different textile based strain sensors for measuring different level of strains were presented. Sensor consist a conductive part formed by coating or weaving technique. Both elastic and inelastic textile substrates were selected to achieve the required stains in applications. Sensor configuration was characterized using a tensile tester and measuring the resistance parallel by microprocessor. A linear working range with transfer function of each sensor was found. Coated sensor gives a good stability, while woven sensor was relative less stable. Inelastic textile substrate reduces the hysteresis error caused by refraction and construction of materials. The sensitivities were between 2.5 to 9 vary with different sensors. This paper finished by a discussion of how to choose sensors with different applications, among which sensor function and processability are most important aspects to be considering.

Key Words: Smart textile, strain sensor, textile integration, conductive yarn, measurement

1. Introduction

Smart Textiles represent the next generation of textiles anticipated for use in many applications. Fibres, yarns and fabric structures with added-value functionality, such as conductivity, sensing and actuating abilities, have been developed for a range of applications, especially in sport and heath care areas. Integration of intrinsic sensing function into textile structures is an elegant way to monitor the human body and/or environment changes. The integration of sensors is not only a concern in clothing industry, but also has a potential in technical textiles applications, for example in the automotive area where the share of textile components is constantly increasing [Drean et al., 2007]. The possibility of using textile strain sensors has been presented in several research projects. This new generation of strain measurement devices have been made for applications, where conventional sensors are not suitable due to their rigid mechanical properties [Cedric et al., 2008].

Strain sensors may be based on several types of principles, most commonly on piezoresistive, and optical. The piezoresistive effect, successfully employed in sensors, can indicate the stress or strain change during time by recording intrinsic resistance change of the material. Optical fibres use another phenomenon, by measuring the path and strength of an optical signal. The advantage with optical fibre sensors is that optical signals effectively eliminate the electrical noises. Many previous approaches have integrated strain sensing properties into the textile structure based on different textile processes. Knitted sensors manufactured from yarns based on carbon [Bickerton, 2003] or metal [Van Langenhove, 2004] have been used for measuring cyclic forces such as breathing rate. Coating or chemical vapour deposition is another method to apply conductivity into textile structure. Conducive elastomeric composites coatings have been shown to have highly sensitive pizeoresistive properties when deformation, such as stretch [Tognetti et al., 2004] or press [Softswitch] is applied. Conductive polymers, such as polyaniline, polypyrolle or polythiophene, are polymers that are inherently able to conduct charge through their polymeric structure, and they have been used as strain sensors in several projects as well [Li et al., 2005; Munro et al., 2008; Tsang et all, 2005 & Dunne et al., 2006]. The integration of piezoelectric PVDF films by means of lamination has also been shown as a potential flexible strain sensor [Edmison et al, 2002]. D.W.Lloyd, D.G.Neilly and D.B.Brook [Lloyd et al., 2001] have succeeded to measure small strain as the normal engineering strain, but the sensor was limited for large strain up from 10%.

In this paper, we present four different textile strain sensors based on different textile manufacturing processes. First, the sensor materials and the textile integration are described. Thereafter the experimental procedure is described, followed by the result. Finally the results are analysed and future efforts are suggested.

2. Sample preparation

The sensors presented in this paper are based on conductive materials which have been applied to the textile substrate by means of coating or integrated into the textile substrate directly in the weaving process, figure 1.

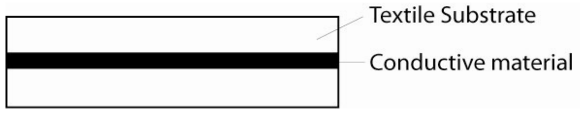

Fig. 1.Construction of textile strain sensor

The textile substrates were both elastic and inelastic woven fabrics. Four types of samples were developed, each of them described below.

2.1 Sample 1, S1 (Fig. 2.)

Textile substrate: Polyamide/Lycra

Conductive material: Silicon rubber filled with carbon-black particles, Elastosil LR 3162 A/B. Supplier Wacker Ltd.

Manufacturing method: Textile substrate: plain weave. Conductive material: knife-over-roll coating.

Sample Size: 200mm x 50 mm, **coated area:** (150mm x 10mm)

Fig. 2. Elastic coated sensor, sample 1(S1)

2.2 Sample 2, S2 (Fig.3.)

Textile Substrate: Cotton (95%) & lycra(5%)

Conductive material: Bekintex 50/2, Staple fibre 80% polyester, 20% stainless steel. Supplier Bekaert

Manufacturing method: plain weave

Sample size: 200mm x 50 mm.

Fig. 3. Elastic woven sensor, sample 2(S2)

2.3 Sample 3, S3 (Fig. 4.)

Textile substrate: Polyester (cargo security strap).

Conductive material: silicon rubber filled with carbon-black particles, Elastosil LR 3162 A/B. Supplier Wacker Ltd.

Manufacturing method: Textile substrate: plain weave. Conductive material: Knife over roll coating.

Sample Size: 200mm x 50 mm, **coated area:** 150mm x 50mm

Fig. 4. Inelastic coated sensor, sample 3 (S3)

2.4 Sample 4, S4 (Fig.5.)

Textile Substrate: Cotton

Conductive material: Bekintex 50/2, Staple fibre 80% polyester, 20% stainless steel. Supplier Bekaert

Manufacturing method: Plain weave

Sample size: 200mm x 50 mm.

Fig. 5. Inelastic woven sensor, sample 4 (S4)

3. Experimental procedure

The samples were measured to determine the relationship between mechanical properties (strain-stress) and electrical properties (resistance) of sensors.

3.1. Measurement setup

The mechanical properties were measured by a tensile tester and by a specific cargo strap testing machine. Sample 1, 2 and 4 were tested in the tensile tester presented in figure 6, and the measurements were done at a speed of 50mm/min. The maximum elongation variance with different sensors refers to the sensor span. Sample 3 was tested by a specific cargo strap testing machine, where a regular force from 100N to 2500N was applied. Each sample was measured five times and the relaxation between measurements was 10 sec.

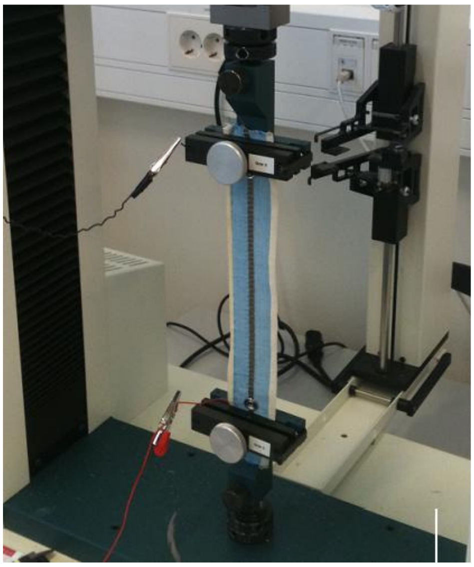

Fig. 6. Mechanical measurement setup

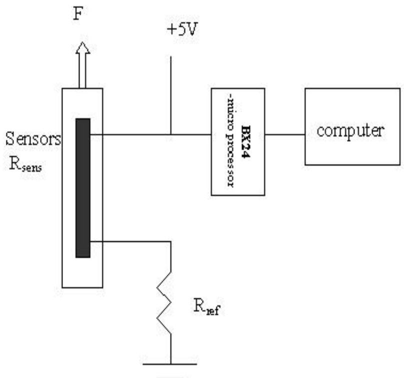

Fig. 7. Electrical measurement setup

In order to determine the electrical and mechanical properties simultaneously, the sensor resistance was recorded by a pre-programmed microprocessor and a computer. The circuit is explained in figure 7. The sampling rate for resistance measurement was 9 samples/ sec, which corresponds to 9Hz in frequency. Snap buttons were used as the interface between textile sensors and electrical wires.

The output voltage measured from the microprocessor was in digital form (D_{out}). It can be calculated into analog output voltage (V_{out}) by the equation: $V_{out} = \frac{5\,Volts}{2^{10}} * D_{out}$

The output voltage (V_{out}) over the reference resistor (R_{ref}) was measured according to Ohm's Law in series circuit. The sensor resistance (R_{sens}) was calculated by:

$$\frac{V_{out}}{R_{ref}} = \frac{5 - V_{out}}{R_{sens}} \Rightarrow R_{sens} = \frac{R_{ref}(5 - V_{out})}{V_{out}}$$

The reference resistance (R_{ref}) was determined in advance, similar to the resistance of the textile sensor.

3.2 Measurement method

Using the described measurement set-up the sensor linear working range (span), working function, sensitivity, stability and hysteresis error were measured.

3.2.1 Sensor span

The sensor span represents the working range of the sensor, which is the determination of the linear input-output relationship. The sensor working function defines the numerical relationship between input and output of the sensor within the linear working range (span). The sensors span and transfer function is determined by simultaneously recording the sensor resistance and elongation.

3.2.2 Sensitivity

The sensitivity of a strain sensor is defined as the resistance change (percentage) divided by the elongation (percentage) during strain. The sensitivity provides the overall sensing property of sensor. The sensitivity of a metal strain sensor is around 2, while the sensitivity of semiconductor strain may be as high as 150.

3.2.3 Stability

The repeatability in short term is called stability, while it is called aging in long term. In this experiment, the sensor performance after 1 hour, 1 day, 5 days and 14 days has been tested, confirming the sensor stability.

3.2.4 Hysteresis

A hysteresis error is a deviation of the sensor's output at a specified point of the input signal when it is approached from the opposite direction [Fraden,J 2007]. The hysteresis before stretch and after release is of interested in our experiment. Sensor has been stretched until the maximum working range and released immediately.

4. Result

In this section, the sensor working range, the transfer function within this working range and the sensor sensitivity are presented. The phenomenon of whether resistance increase or decrease with extension has also been analyzed. Further, the sensor stability and hysteresis errors were illustrated and compared.

4.1 Sensor linear working range (Span)

Linear working range of textile sensors depends on the properties of the textile substrate and how the conductive part has been integrated into textiles. The elastic samples had a larger span than the rigid samples. But the conductive coating increased the span due to the excellent elasticity of the silicon rubber. According to the curves in figure 8, the span of elastic coated sensor ranges between 5% to 40 %(10mm elongation and 80mm elongation to the original length of 200mm). The inelastic coated sensor performed below 6% (12mm). In the woven samples, a linear working range of the elastic sample is 3.5% to 5% (7mm to 10mm), while the inelastic sampled had a working range between 1% and 2.5% (2mm to 5mm).

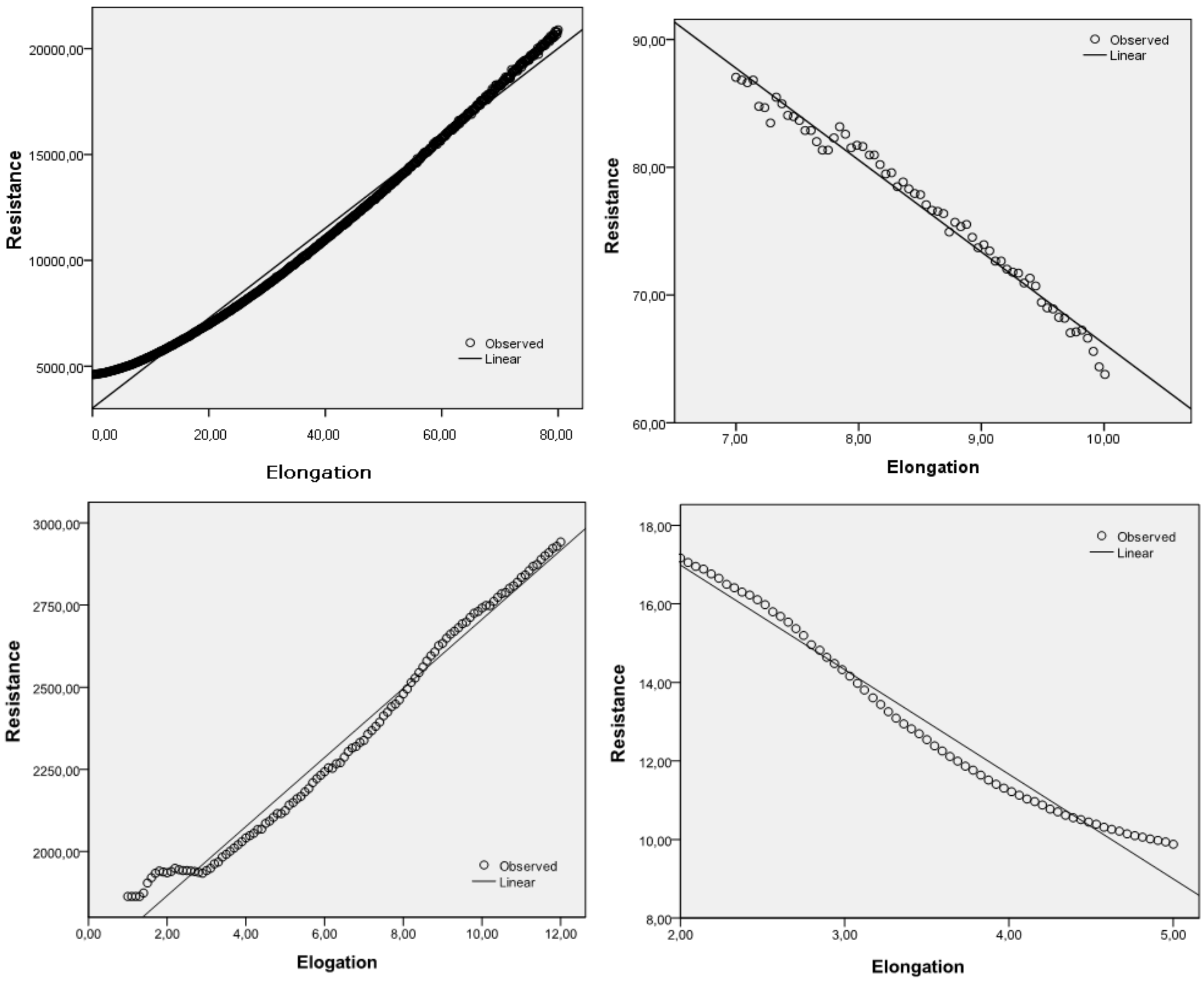

Fig. 8. Linear working range of elastic coated, S1(top left), elastic woven (top right) inelastic coated , S3 (bottom left) and inelastic woven,S4 (bottom right) sensors.

4.2 Sensor Transfer function and sensitivity

As illustrated in table 1, the coated sensors have positive resistance versus elongation change effect, which means that the resistance increases with extension. However, the woven sensors shown opposite phenomenon, the resistance decreases when the elongation is increased.

The reason for that is the construction of different samples. In the coated sensor the conductive effect comes from the presence of carbon black particles. When the sensor is released, the carbon particles are evenly distributed in the silicon rubber and tightly contacted with each other as in figure 9 (left). When the sample is stretched, the carbon particles are pulled apart that some of the carbon black particles contact with nothing. Therefore the conductive path becomes narrow and the resistance will increase.

Table 1: sensor transfer function and standard error.*: standard error refers to an estimate of standard deviation, derived from a particular sample used to compute the estimate.

Sensor	Name	Parameters		Std. Error*	Transfer function
1	Elastic Coated	Constant	1700,651	445,518	Y=1700,651+230,382X (+error)
		Elongation	230,382	8,9	
2	Inelastic Coated	Constant	1655,178	9,650	Y=1655,178+105,156X (+error)
		Elongation	105,156	1,332	
3	Elastic woven	Constant	138,078	1,093	Y=138,078-7,189X (+error)
		Elongation	-7,189	0,128	
4	Inelastic woven	Constant	22,842	0,205	Y=22,842-2,776X (+error)
		Elongation	-2,776	0,057	

The woven sensors have different principle to achieve conductivity. As shown in figure 9 (right), the conductive yarns woven in the central part of the sensor form the conductive path. When the sample is stretched, the conductive wefts are tightened to each other. The conductive connections increase and the resistance decreases.

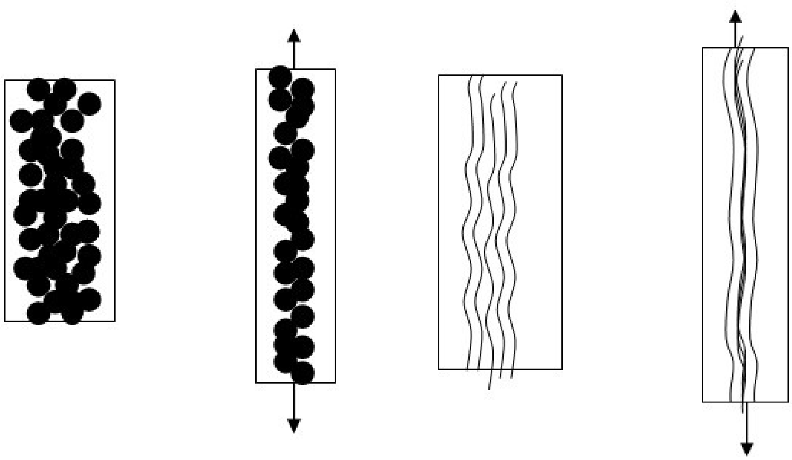

Fig.9. Conductive path of coated sensor (left) and woven sensor (right) before and after stretching.

The sensitivity quantitatively indicates the sensors mechanical-electrical behaviors and the sensitivity usually specified by gauge factor, GF. Gauge factor can be calculated by $\frac{\Delta R/R}{\Delta L/L}$.

By calculation, the elastic coated sensor had the highest GF equal to 9.2, the inelastic woven sensor had the lowest GF in absolute which was around 2.5. The GF in inelastic coated sensor and elastic woven were 8.5 and 6 respectively.

4.3 Stability

All sensors have acceptable stability after one hour, one day, five days and two weeks repeated measurements. Both elastic and inelastic coated sensors have almost constant performance regardless to the time, confirming the stability of sensor. Concerning the woven sensor, the minimal resistance shows a marginal decreasing along with time of about 10% in elastic woven and 25% in inelastic woven. The result of elastic coated sensor stability change during 2 weeks is shown in fig. 10 (left), while the right one shows the change of in elastic woven sample.

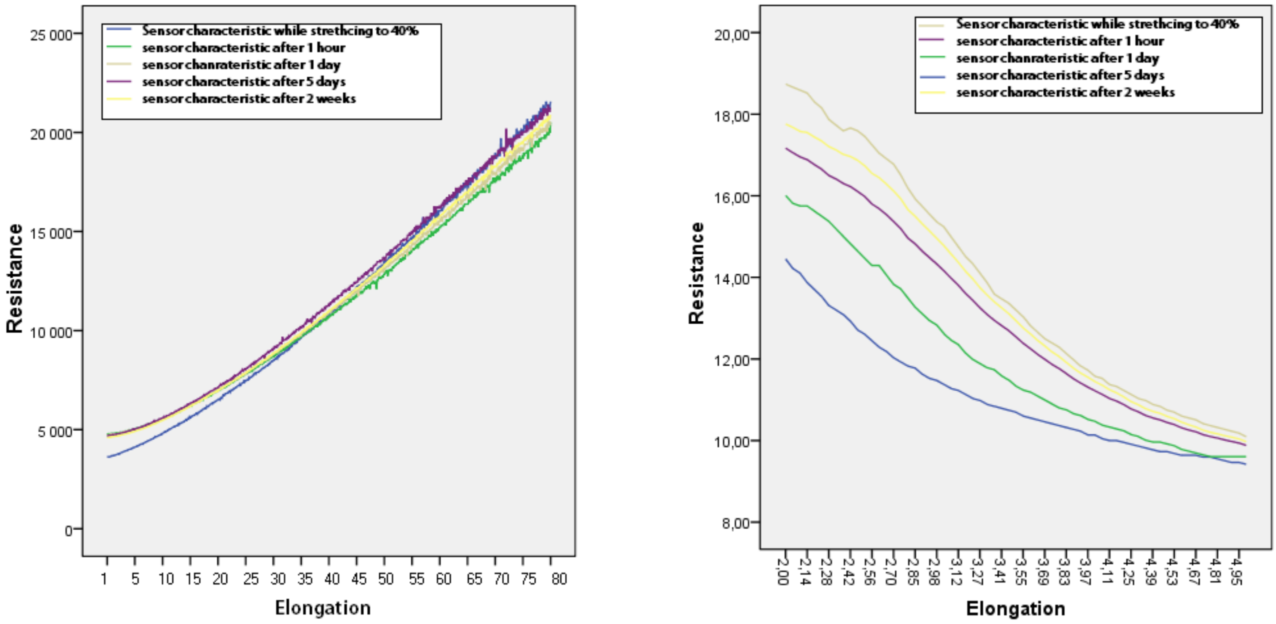

Fig. 10 Stability test during 2 weeks, elastic coated sensor, S1 (top) and inelastic woven sensor,S4 (bottom)

4.4 Hysteresis error

The resistance versus strain under a typical stretch and release cycle plot, figure 11, shows an example of how to calculate the hysteresis error of the sensor. Hysteresis is typically caused by friction and structural change in materials [Fraden,J 2007]. Usually elastic materials have higher hysteresis. This is because elastic materials need longer recovering time, especially when high force is applied.

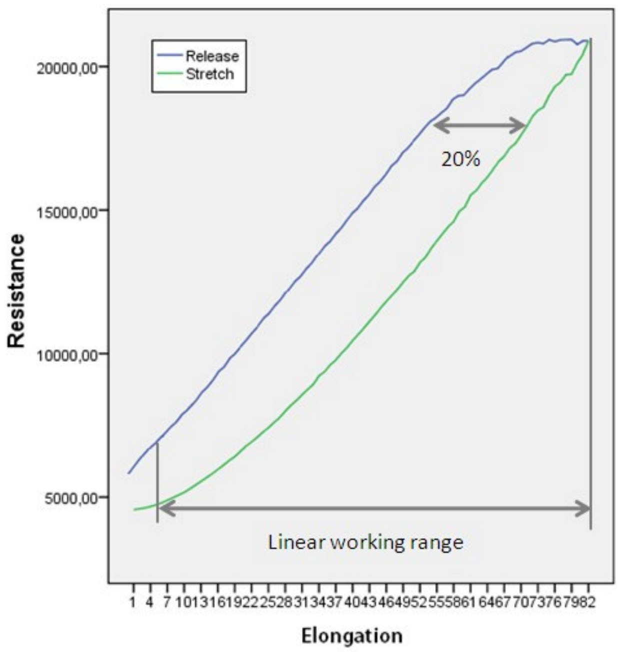

Fig.11.Hysterisis error of elastic coated sensor, S1

The hysteresis error for elastic coated sensor (see fig.11.) and elastic woven sensor were rather high, which were around ±10% (20%) and ±9% (18%) of the working range. Inelastic woven has smallest hysteresis error; it has only 1.9% deviation. Inelastic coated sensor in our case had large hysteresis around 20%, this caused from the large force (2,5ton) applied on sample. When large force involved in, the textile substrate changed not only in fabric structure, but also in arrangement of yarns. Elongations applied on single yarns were more difficult to recover.

5. Discussion and Future work

This project presents four different textile strain sensors and each sensor has been characterised by measuring the mechanical and electrical performance during stretch. Two of the sensors were based on elastic textile structure and the other two sensors were based on rigid textile structure. The result shows that in textile strain sensor development, the requirement of the sensors properties such as the maximum elongation, sensors force, stability and hysteresis depend upon the end application. The quality and the processability are other important issues to consider in the sensor development.

The working range of sensors shows that the different sensors are useful in different applications with different requirements of elongation at maximum. The elastic woven sensor (sample 2) senses strain up to 6% while the other elastic senor, conductive silicon coated on elastic fabric senses strain up to 40%. The rigid sensors on the other hand only sense small strain up to 2%.

The stability of the coated sensors had almost constant performance while the resistance of the woven sensors decreased. The reduction of resistance was quite small and may derive from the influence of the environment. However, the fact that the resistance decreases the initial resistance should be calibrated in advance.

The inelastic samples had less hysteresis error compared with the elastic samples. Therefore, the inelastic textile sensor should be chosen when rapid cyclic force should be monitored.

Besides the mechanical and electrical properties of the sensors, processablility and quality are important issues to consider when designing a textile strain sensor. The silicon rubber used in this project is quite hard to apply by using conventional coating technologies due to its solid state compared to fluid coating materials. However, conductive coating is an economical process when textile substrate is already made. Weaving the sensors by using a strain sensitive yarn or fibre seems to be an easier process and the development of fibres and yarns that could be used as stain sensors in yarn-based processes is of high interest in this area

The next step of this project is to test the sensors in different climate conditions. Modification of temperature and humidity may influence the performance of the sensors. Modeling is another area of interest that could verify the experimental results and eventually push the standardization of textile sensor manufacture and testing methods forward. Accordingly new testing methods and devices need to be introduced in development and evaluation of the smart textile products in order to achieve higher accuracy. An important issue to be considered is that the required characteristics of smart textile products are highly dependent on the end application.

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