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The System Integration of Flexible Electronics into a Soft Exoskeleton

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Abstract

In order to make exoskeletons more useful for a larger variety of users, especially within healthcare, it is of utmost importance to improve its wear ability. The scope of the XoSoft project is to develop a soft, wearable and comfortable soft exoskeleton. Here we describe the partial research on the integration of textile sensors for the XoSoft soft exoskeleton. Various resistive textile sensors for knee-sensing were made. All sensors show repeatable results however, their accuracy and usability for this project are questionable.

Keywords

Smart Textiles; Sensors; Exoskeleton; Electronics

Introduction

The XoSoft project focuses on the development of a soft exoskeleton, in form of a trouser that can assist people in walking with mobility restrictions due to muscle weakness or partial loss of sensory or motor function. In contrast to the existing exoskeletons, developments in this project are not intended to achieve functional recovering, but to assist the user in a tailored manner. The trouser comprises sensors, actuation, power and a controller. In addition to provide lower limb assistance, it monitors lower leg movement kinematics and classifies the data to monitor mobility levels and activity type. In this vision, sensor signals will be basis for feedback in case of impaired balance due to weakened proprioception. Used sensors should be made of soft materials, which result in high deformations, extensibility, compliance, and conformance. The sensors are fully integrated in the textile garment, which demands for specific structure and fabrication technology. The main reason for such requirements is to avoid rigid parts that would limit movements of the user, and because the final garment should be worn under clothes, being comfortable as well as easy for a person to put on and off. Because of the multi-disciplinary and high technology level of the XoSoft project, a system engineering approach is being used. System engineering is an interdisciplinary approach and means to enable the realization of successful systems. Within the project several prototypes will be developed and tested against a broad range of user requirements, which are listed in the first year of the project [1]. Users descriptions were made as a red lining within the project and with each prototype a test cycle with these users (either theoretically/lab scale or actual subject testing) will be performed. Because of the immediate need to apply flexible, "textile" sensors into the first (Alpha) prototype, not only a review of scientific research, but also a review of commercially available sensors was performed. Within this paper, first the commercially available sensors will be discussed. The theoretically proven to be used commercially available sensors will first be tested for usability for the XoSoft project (so compared to the developed user requirements) on a lab-scale base.

Analysis of Commercially Available Solutions for Soft Sensing

Among all kinds of wearable sensors, in this short analysis, we will focus on those able to detect parameters related to mechanical stimuli, such as strain and pressure, induced by, e.g., bending or indentation. All these devices need to be flexible and made of soft materials, conformable with curved surfaces and, in most of cases, also stretchable. Strain sensors are the most common mechanical transducers; their deformation causes a variation in an electrical quantity, which is the output signal of the device. Indeed, other mechanical quantities (i.e. bending angle in a joint) are often evaluated from the strain to which the sensor is subjected. In particular, flexible and stretchable strain sensors can be classified in two main categories: resistive and capacitive-based.

Textile-based commercial sensors

Among commercial solutions, in the last years there has been an increase of textile-based sensors and sensing arrays both for pressure and strain detection, and by employing capacitive or resistive transduction mechanisms.

Adafruit [2] developed the conductive rubber cord stretch sensor with 2mm diameter and 1 meter long made of carbon black impregnated rubber. In a relaxed state the resistance of the sensor is about 350 Ohms/Inch, when stretched, the resistance increases. When a 6" piece of ~2.1 Kohms is stretched to 10" the resistance will become ~3.5 Kohms. With its high flexibility and small diameter the rubber cord sensor could be integrated into knitted or woven fabrics quite easily. Literature shows us various examples of conductive yarns which were used as pressure or stretch sensors. For example knitted conductive wires used as stretch sensors [3], PPy-coated Lycra is used as sensitive strain gauge material [4] and thermoplastic elastomer doped with 50% by weight of carbon black is used as a sensor thread [5]. The EU-funded projects Wealthy and MyHeart also delivered various sensor fabrics [6]. All development describe different types of yarns with various properties, stainless steel yarns show resistance to corrosion, biological inertness, they are widely available as textile yarn and with low cost-price however, they are difficult to integrate into textiles using conventional production processes. Yarns produced from polymer material, infused with carbon black or silver/gold/copper coated yarn are more suitable to use in conventional production processes however, they are less robust and more sensitive for weather [7,8].

Conductive yarns are used for several commercially available stretch sensors. Pressure Profile Systems [9] offers the TactArray® System – comprising capacitive sensors (1 mm thick) constructed

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from soft and flexible conductive cloth, and capable of resolving pressures of about 10 Pa – and the Stretchable TactArray® System – including capacitive sensors (3 mm thick) made of silver-metalized Lycra, able to stretch to 10% and to detect pressures up to 207 kPa. Sensor Products (Madison, NJ, USA) proposes the Contact Surface Pressure Mapping, a resistive pressure sensor array, employing highly conformable and elastic conductive textile as constituent material, with a thickness of 180 μm and a pressure range between 0.7 and 1379 kPa. Another interesting example that can be found in the market was provided by StretchSense® (Auckland, New Zealand), which developed a capacitive-based strain sensor, named Fabric Sensor®, made of conductive fabric and able to sustain strain up to 80%. Also LG Innotek (Seul, Korea) announced in July 2016 the development of a new concept of textile flexible pressure sensor, made of highly elastic polyurethane material, and employing the capacitive transduction mechanism. However, this product is not yet commercially available.

Film- based bending sensors

An already commercially proven technique of bendable sensing is using flexible film sensors. These sensors are not flexible at most of the times or stretchable, but are narrow and small so it is possible to integrate them into stretchable, breathable fabrics. For example the 2.2”, a small sensor used for angle displacement measurement. The flat resistance of the sensor is 10KΩ ± 30% and the bending resistance is a minimum of 2 times greater than flat resistance at 180° pinch bend, power rating is 0.5 Watts continuous, 1 Watt peak. Because of the limited size (will not influence the existing textile properties of the XoSoft pants) of the sensors and its accuracy it is theoretically possible to use these sensors as force sensors in the XoSoft pants. Further testing will be done by IIT to verify if the sensors will be practically usable for the XoSoft pants. Spectra Symbol bending sensors are used frequently in textile applications as for example VR gloves from Manus VR and have shown its applicability and robustness in these applications [10,11] (Figure 1a, 1b).

In conclusion on this state of the art research, as many commercial electronic systems are available and could be connected to any clothing, a textile wearable system becomes more feasible. However, electronics with capability of true integration in stretchable, breathable textile products with specific soft, lightweight demands are scarce and often limited in reliability and accuracy. Theory shows that few sensors could be usable for the XoSoft project, a few existing sensors have been chosen to be integrated into prototypes; The Adafruit rubber cord stretch sensor, which is easy to integrate into a textile fabric; the Spectra Symbol flex sensor because of their combination of small surfaces and high accuracy and conductive yarn as sensors where tested because of their high flexibility in design and numerous options for integration. When integrated into textiles, these wearable sensors must maintain their sensing capabilities under the demands of normal wear, which can impose severe mechanical deformation of the underlying garment/substrate.

Testing and Results

Conductive yarn stretch sensor

Literature states that it is theoretically possible to use conductive yarn as resistive stretch sensor (2.1 Textile based commercial sensors) because these yarns show the best compatibility with existing textile materials, it is the most preferable option to integrate in fabrics when considering comfort and flexibility. In order to evaluate whether this method could be useful for the XoSoft project various conductive yarns where tested as resistive sensors. Two types of conductive yarns where chosen to integrate into textile as a sensor. The most suitable yarn was used in the final sample prototype. Material selection was based on the sufficient conductivity to reach objective, Biocompatible (non-irritating), ability to resist contact with human skin & sweat (could also be solved by isolating), Produce ability and Reproducibility.

Apparatus and materials: Sewing machine: Pfaff Classic Style Fashion sewing machine; Fabric: commercial elastic textile; Solo fleece: a sample of this fabric of 32cm X 22cm is temporarily added to the knitted fabric to prevent stretching. After sewing the solo fleece fabric is dissolved in water; Grey Yarn: Bekintex fibres tech 48505 BK 50/2 Cones of 530g P376602; Gold Yarn: Shieldex 100% silver-plated nylon 117/17 2ply. Resistance 100Ω/10cm; Strength tester: Tenso Lab semi-automatic strength tester with pneumatic grip clams; Multi-meter: Green-Line Voltcraft VC270. Conductive yarn has certain resistance (mentioned at materials). Its resistance varies at different length. Higher is the length, higher the resistance. When used as stretch sensor, the yarn must be stitched in a zig-zag stitch (this stitch will provide stretch ability in the sensor) the stitch density (stitches/cm) will influence change in resistance. The resistance of the yarn is not entirely linear, because a yarn is composed of filaments and staple fibres that are interconnected. This results in a conducting system that contains of many interactions and contact points. It is not clear how density will affect resistance therefore conductivity measurements in conductive yarns need to be done in order to fully describe the character of a conductive yarn. However, if a conductive yarn consists of a linear metal fibre as a conductor, then of course the conductivity is linear. But in this case, if we incorporate these filaments in textiles, due to the curvature and mechanical stresses exposed during production process it may lead to non-linear behaviour. Properties of the seam that influences the resistance during stretch are stitch density, stitch length, stitch amplitude and yarn properties. Different stitch lengths and widths will be tested to see where the resistance will change the most and most repeatable (Table 1 and Figure 2).

The samples are placed between clamps of the Tenso Lab strength tester, with a space between the clamps of 16cm. Resistance is measured 3 times for each seam when the fabric is relaxed. Then, separating the distance between the clamps from 16cm to 20cm stretches the fabric. Again the resistance is measured 3 times for each seam. Mean values for relaxed and stretched fabrics are presented in Tables 2 and 3.

Rubber cord stretch sensor

The Adafruit commercial conductive rubber cord stretch sensor

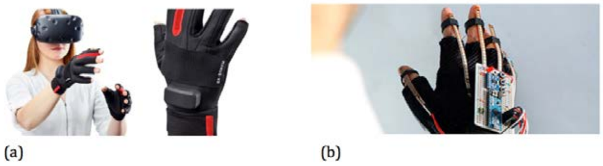

Figure 1: (a) Spectra Symbol bending sensors integrated into VR-gloves from Manus-VR (b) Earlier VR- glove prototype.

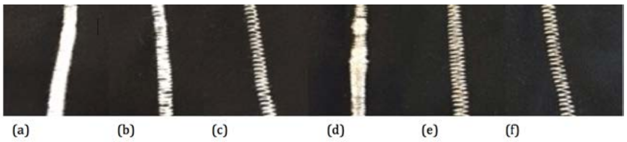

Figure 2: Used seams; seam 1 (a); seam 2 (b); seam 3 (c); seam 4 (d); seam 5 (e); seam 6 (f).

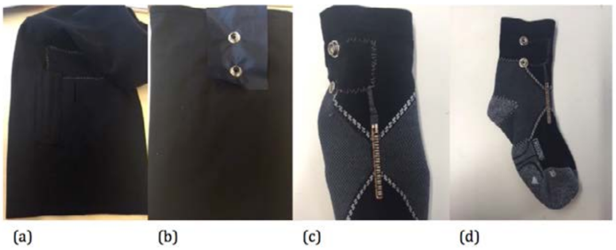

Figure 3: Spectra symbol flex sensor integrated in; knee pad outside (a) inside (b); sock front (c) side (d).

Table 1: Variation of seams used for sample 1 and 2.

Sample	Seam	Yarn	Stitch type	Stitch length	Stitch width	Yarn tension
1	1	Bekintex	3	6	0,4	1
	2				0,6	
	3				0,8	
2	4	Shieldex	3	6	0,4	1
	5				0,6	
	6				0,8	

Table 2: Measurement nr.1 (mean value of 3).

Sample	Seam	Stitch width	Yarn	Resistance [Ω] not stretched	Resistance [Ω] stretched 25%
1	1	0,4	Bekintex	6,693 KΩ	6,683 KΩ
	2	0,6		4,143 KΩ	3,770 KΩ
	3	0,8		2,782 KΩ	1,913 KΩ
2	1	0,4	Shieldex	52,4 Ω	70,0 Ω
	2	0,6		109,1 Ω	118,6 Ω
	3	0,8		104,9 Ω	107,0 Ω

Table 3: Measurement nr. 2 (mean value of 3).

Sample	Seam	Stitch width	Yarn	Resistance [Ω] not stretched	Resistance [Ω] stretched 25%
1	1	0,4	Bekintex	14,85 KΩ	15,82 KΩ
	2	0,6		5,42 KΩ	5,53 KΩ
	3	0,8		5,77 KΩ	5,99 KΩ
2	1	0,4	Shieldex	64,1 Ω	80,3 Ω
	2	0,6		116,4 Ω	120,1 Ω
	3	0,8		104,2 Ω	106,4 Ω

Table 4: Bending resistance variation (mean value of 3).

Measured at:	No bending	Bending +45°	Bending -45°
Stretch sensor	27,27 KΩ	44,7 KΩ	24,92 KΩ
Connected yarn	27,86 KΩ	65.77 KΩ	25.86 KΩ
Push buttons	29.54 KΩ	71,33 KΩ	25,81 KΩ

was integrated in a fabric to produce different prototypes of a knee/ankle braces. The rubber cord was integrated during the knitting process during the fabrication of the textile. Two samples were produced in kneepad shape inorder to test real time knee-sensor capabilities.

Apparatus and materials: Sample 1: Knitted on two beds; Gauge = 18; Gauge in sensor rows (2) = 19; Used Yarn: 2 Ply twisted grey cotton staple fibre; Sample 2: Knitted on two beds; Gauge = 20; Used Yarn: 2 Ply twisted grey cotton staple fibre / Elastane;

Yield and difficulty of production: The fabric showed a good stretch and recovery to be used as a brace. The fabric surrounding the sensor showed some wrinkles, probably due to the surface roughness of the rubber cord. Using a looser knitting pattern or wax to soften the surface of the rubber cord could possibly solve these issues.

Conclusion of knitted samples: In prototype nr.1 the knitted fabric did not show good recovery to be used as a brace. All prototypes show wrinkles where the rubber cord stretch sensor was integrated because of its surface roughness it is not able to slide through the fabric. In prototype nr.3 a more open structure was tested to reduce wrinkling, however this fabric showed poor recovery. At this moment, recovery is more important than wrinkling what will only affect the visual part of the prototype so this can be altered after the working principle is proven. This is why prototype nr. 2 is chosen to be further developed.

Spectra Symbol flex sensor

The Spectra Symbol flex sensor was integrated in a fabric, including a conductive yarn (copper/silk yarn) sewn in zigzag pattern for the electrical connections. A kneepad, as well as an ankle pad, was made with an integrated flex sensor. The kneepad was made using fabric as base material, for the ankle pad a sport sock was used as base material. The flex sensors were sewn on the fabric/sock and a conductive copper silk wire was used as conductive track to the push buttons.

Apparatus and materials: Fabric: Knitted fabric and woven fabric were used for the kneepad. A sport sock was used for the ankle pad; Sewing machine: Janome Cover Pro 1000 CPX machine (4 yarns); Sewing machine: industrial lock machine (3 yarns); Push buttons: Prym Sport & Camping 15mm Ø (art. 390900); Stretch sensor: Flex sensor 2.2" (Spectrasymbol). Flat resistance of 10 KΩ ± 30% is applied. Bend resistance when the device is bent was at least 2x greater than the resistance of flat device; Conductive Yarn: Scientific Wire company 9/0.040mm silk covered stranded copper litz wire; Multi-meter: Green-Line Voltcraft VC270; Soldering iron and solder.

Yield and difficulty of production: The copper wire contains, silk yarn outer layer, another protective coating under it. This needed to be removed to measure conductivity and to get a proper connection to other conductive parts. The coating dissolves when the yarn is heated up, and when tin is applied. It is easier to first remove the coating by applying a thin layer of tin on the yarn before sewing the yarn to the fabric. Further developments could include more efficient production steps; using for example technical embroidery. Some basic tests were performed on the kneepad with integrated Spectrasymbol flex sensors, only to see whether the stretch sensor would react to bending. Further testing will follow. A test procedure was implemented for measuring resistance. The stretch sensor response was measured 3 times, and the mean values are reported in Table 4: before applying bending, and after a +45° and -45° bending, respectively.

Results show that the measurements are repeatable. The measurement of +45° bending at stretch sensor show an average increase of ~17KΩ with a repeatable accuracy. The -45° bending however does not show any significant change in resistance this is to be expected because the material is pushed into a non-stretch situation and when going the +45° the material goes into a stretch situation, which means the sensor works one way. The measurements at yarn point and push button show the connectors influence the resistance of the sensor. However, the difference between no bending and bending +45° is still significant and repeatable. Further testing will have to be performed to prove if the sensor will be suited for the Xosoft pants.

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Conclusion

Preliminary results showed that conductive yarn as a stretch sensor could give repeatable results. The flex sensor shows an average increase of ~17KΩ when bend +45° (Figure 3). The rubber cord sensor showed repeatable results when stretched (Figure 2). All sensors however possibly do not show enough accuracy. Further research is focussed on usability of textile resistive sensing in the XoSoft pants or whether capacitive or other sensors would give more meaningful measurement.

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