TEKSTİL VE MÜHENDİS

(Journal of Textiles and Engineer)

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Development of Textile-Based Resistive Pressure Sensing Structures for Wearable Electronic Systems

Giyilebilir Elektronik Sistemler için Tekstil Bazlı Rezistif Basınç Algılayıcı Yapıların Geliştirilmesi

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Online Erişime Açıldığı Tarih (Available online):30 Haziran 2018 (30 June 2018)

Bu makaleye atıf yapmak için (To cite this article):

Özgür ATALAY (2018): Development of Textile-Based Resistive Pressure Sensing Structures for Wearable Electronic Systems, Tekstil ve Mühendis, 25: 110, 140-145.

For online version of the article: https://doi.org/10.7216/1300759920182511009

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Araştırma Makalesi / Research Article

DEVELOPMENT OF TEXTILE-BASED RESISTIVE PRESSURE SENSING STRUCTURES FOR WEARABLE ELECTRONIC SYSTEMS

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Gönderilme Tarihi / Received: 31.01.2018
Kabul Tarihi / Accepted: 04.05.2018

ABSTRACT: The aim of this research work is to develop textile-based resistive soft pressure sensing structures. In order to achieve this aim, two conductive knit fabrics are separated by non-conductive mesh fabric. Working mechanism of the sensors rely on gradual contact of the conductive fabrics through the mesh fabric thereby changing the electrical resistivity of the structure. Proposed sensors are compliant, flexible and easy to produce. The initial electrical resistance of the soft resistive sensors was measured before any applied load. It was observed that sensors were non-conductive. This indicates that sensing structures could also be utilized as flexible pressure switches. Effect of mesh size on sensitivities and working range of the sensors are also investigated. It was found that while bigger mesh size contributes the higher sensitivity, it reduces the working range of the sensor. However, this property can be utilized to adjust sensitivity and working range of the sensor for targeted applications.

Keywords: Soft sensors; textile-based sensor; pressure sensors; electronic textiles

GİYİLEBİLİR ELEKTRONİK SİSTEMLER İÇİN TEKSTİL BAZLI REZİSTİF BASINÇ ALGILAYICI YAPILARIN GELİŞTİRİLMESİ

ÖZET: Bu çalışma tekstil yapılı rezistif yumuşak basınç sensörlerinin geliştirilmesini amaçlamaktadır. Bu amaca ulaşmak için iletken örme yapılı kumaşlar iletken olmayan gözenek yapılı kumaşla ayrılmıştır. Sensörlerin çalışma prensibi uygulanan basınca karşılık olarak iletken kumaşların gözenekler vasıtasıyla birbirine değmesi ve bunun sonucunda yapının elektriksel iletkenliğinin değişmesine dayanmaktadır. Öngürülen sensörler yumuşak yapılı, esnek ve kolay üretilebilirdir. Herhangi bir basınç uygulanmadan yapılan ölçümlerde sensörlerin elektriksel iletkenliğinin olmadığı bulunmuştur. Uygulanan basınç sonucu iletken hale gelen sensörler elektronik tekstil devrelerinde aynı zamanda anahtar olarak ta kullanılabilir. Gözenek büyüklüğünün sensörlerin hassasiyeti ve çalışma aralığına etkisi ayrıca incelenmiştir. Bunun sonucunda geniş gözenekli yapıların yüksek hassasiyet ve daha dar bir çalışma aralığı sağladığı bulunmuştur. Sensörün bu özelliği hedeflenen uygulamalar için hassasiyeti ve çalışma aralığını ayarlamaya olanak sağlar.

Anahtar Kelimeler: Yumuşak sensörler; tekstil yapılı sensörler; basınç sensörleri; elektronik tekstiller.

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DOI: 10.7216/1300759920182511009, www.tekstilvemuhendis.org.tr

1. INTRODUCTION

There is an increasing demand in the development of wearable electronic systems for use in human body motion monitoring [1] or physiology monitoring for medical diagnosis [2], sports training [3] or entertainment purposes [4]. Textile structures plays important role for the development of such structures due to their inherent properties such as flexibility, stretchability, breathability and so on [5]. Moreover, textile based platforms behave a second skin and does not restrict the wearer's mobility and comfort. Thus, most current research efforts focus on using of textile based structures to create wearable electronic platforms that are specifically called electronic-textiles [6]. Generally, these systems consist of a number of different components that fulfil different tasks within a system. The types of these components may vary depending on the application area of the structure. However, most electro-textile structures require specific categories of component in order to perform their task reliably: sensors/electrodes, power supply, a communication network within the structure and/or externally, a data processor and an actuator are the basic elements of the system [7]. Among these components, sensors are the key input interfaces for electro-textile systems. In general they can be described as devices that detect a change in physical stimulus and turn it into a signal that can be measured or recorded [8].

One of the growing research areas of textile-based sensors is the creation of pressure sensing structures [9-12]. There are different methods that may be adopted to produce textile-based pressure sensors such as capacitive sensors [13], piezoelectric materials [14], using conductive particles within compressible structures [15] and resistive sensors [16]. The working mechanism underlying capacitive sensors is the same as that for traditional capacitive sensors. Two conductive panels are separated from each other by dielectric material. Production of the plates can be achieved by applying textile production techniques such as weaving [17], embroidering [18] or knitting [19]. Conductivity can be imparted into the plates by embedding conductive yarns into the structure [20] or using coating and printing technology [21]. Foams or spacer fabrics can be used to create dielectric materials. Hoffmann et al. showed that foams and spacer fabrics show hysteresis behaviour during experimental tests [22]. However, hysteresis of spacer fabrics is relatively small compared with that of foams. Also, Hasegawa et al. developed capacitive sensors at the yarn level [23]. Firstly, they created artificial hollow fibre that was manufactured from silicone rubber tube by laminating layers of metal and insulation on the surface. Then, they used these fibres to create pressure sensing woven structures. In their system, the contact force between the intersecting hollow fibres was detected by measuring the capacitance change between the two intersecting fibres. However, main challenges with the capacitive systems are the complexity of the measurement circuitry and the cross-talk problem during the measurements that affect the signal output reliability. Using piezoelectric materials is another route for the creation of pressure sensing structures [24]. The working principle of these structures is on the basis of the generation of an electrical signal depending on the applied pressure. However, piezoelectric systems produce signal output under the dynamic conditions only and they do not generate electrical signal under the static conditions. Thus, this is the limiting factor of these systems to be used in wearable electronic systems. Dunne et al. developed a foam-based pressure sensor [25]. They used polyurethane foam that was coated with polypyrrole. The foam sensor exhibited piezo-resistive reaction when exposed to electric current. The pressure sensitive structure was used to measure shoulder movement, neck movement, breathing and scapula pressure when worn beneath clothing but the sensing structure showed some deficiencies, such as oxidation of the conductive material which affected the consistency of the sensor.

The working principle of resistive pressure sensors is a change in resistance in response to applied pressure. Li et al. designed a woven structure based on a flexible resistive pressure sensor [26]. They used electrically conductive yarns as warp and weft yarns and created a pressure-resistance relationship based on the electrical equivalent circuit model and physical laws. They showed that a sensor woven from fibres with high hardness might be expected to offer a relatively large pressure sensing range in comparison to fibres with low hardness. However, the main drawback of the system is its poor elastic recovery that originates from the inherent properties of the woven structure. Wang et al. created a resistive pressure sensor by sandwiching a coated conductive fabric between two tooth-structured conversion layers of silicon elastomer [27]. Repeatability and sensitivity of the sensors at room temperature were sufficient. Also, modelling and experimental results of the sensor agreed each other. However, manufacturing of silicone part is complex which require chemical process and moulding process.

In this work, fast and easy fabrication of a flexible resistive pressure sensor made with knit conductive fabrics and mesh fabrics is demonstrated for wearable electronic applications. Effect of mesh size on sensing properties was also investigated by the use of two different mesh fabrics. The following section gives details of materials and production of soft pressure sensors, followed by the testing methodology used to determine the electromechanical properties of the resistive pressure sensors. The third part of the paper reports the results promotes a discussion of the electro-mechanical properties of the sensors.

2. MATERIALS AND METHODS

2.1. Materials

For the construction of resistive based sensors, conductive stretchable silver-plated knitted textile (Shieldex Medtex-130, V Technical Textiles Inc., USA) was purchased. Thermoplastic film (3914 Sewfree Tape, Bemis Associates Inc. USA) was used as an adhesive to bond the sensors' layers together. Two types of polyester mesh fabric with different mesh size) were used as separation layer between conductive fabrics. Polyester fabrics were chosen to due to their high resiliency and resistance to wrinkling. Since the proposed sensors will be subjected to repeatable forces during the real life applications, this property is important. Silver-plated nylon yarn with 235 dtex fineness and 100 ohm/m linear resistance (Shieldex 235/34f-HC High Conductivity, V Technical Textiles Inc., USA) used to build conductive connection lines.

2.2. Methods

2.2.1 Manufacturing of the sensors

Figure 1 shows the manufacturing process of resistive based soft pressure sensor. First, conductive knit fabrics, non-conductive mesh fabrics and adhesive tape are cut to designed size (characterization standard of 20 mm x 20 mm) by a laser (VLS 6.60, Universal Laser Systems, USA). However, mesh fabrics are cut 1 mm larger than conductive fabrics in order to prevent contact of conductive fabrics from the edges. Thereafter, each component of the sensor is placed as shown figure 1a and components are bonded each other thermally. As a final step, secure, robust and flexible electrical connections are established as shown in figure 1b. Herein, conductive silver plated nylon yarns are fixed at each side of the sensor by using thermal seam tape. For this purpose, seam tapes are pressed at 120 °C for 10 s with iron. Working principle of the sensor is shown in figure 1c, when the external force is applied on sensor surface, top and bottom layer conductive fabrics make contact each other through the holes in mesh fabrics, thereby electrical resistance of the structure changes.

In this study, sensors are constructed with two different mesh fabric that have two different mesh sizes (first type has hole size; with the dimension of 594±7µm X 437±19µm, second type has hole size; with the dimensions of 1346±62µm X 1154±25µm) in order to see effect of mesh size on sensing properties. Figure 2 shows real image of the sensor with connection lines as well as the magnified image of the sensor components.

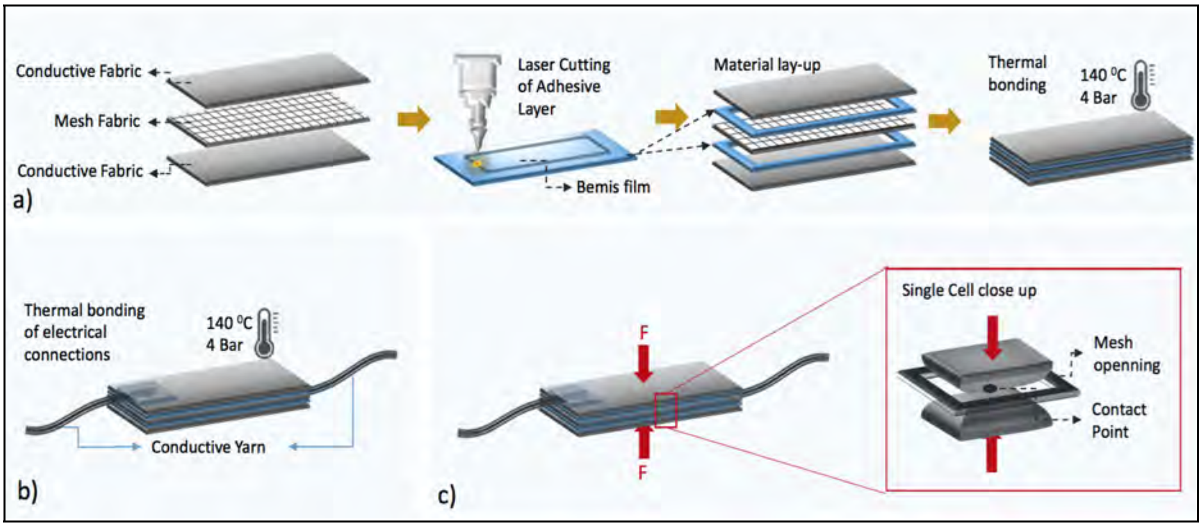

Figure 1. Manufacturing steps of soft sensor (a-b) and working principle of the sensor (c)

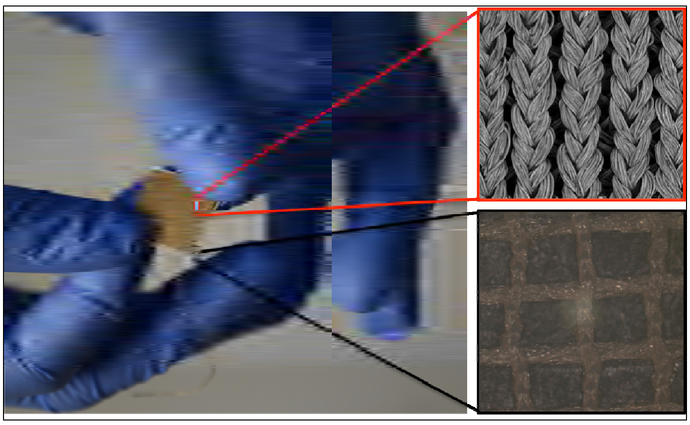

Figure 2. Manufactured soft sensor and its components (magnified image of conductive knit fabric and mesh fabric)

2.2.2. Testing methodology

An experimental setup as shown in is developed to collect mechanical and electrical data, using a mechanical tester (Instron 5544A, Instron, USA) and a precision digital multimeter (Keysight 34465A) in order characterize the electrical signal output of the resistive sensors to applied pressure as shown in figure 3.

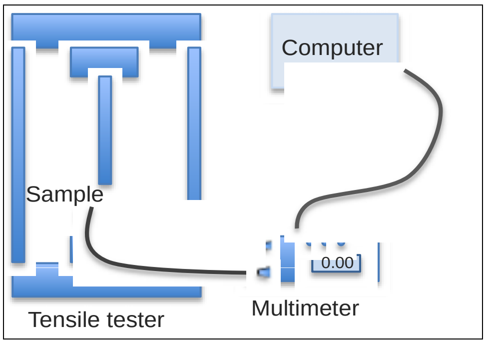

Figure 3. Experimental set-up for electromechanical; characterization

Four-probe measurement method is used to the measure electrical resistance in order to eliminate effect of contact resistance. A vertical load is applied in a direction normal to the sensor surface. Soft resistive sensors used for characterization were 20 mm ×20 mm in total area with a thickness of 0.8 mm. It should be noted here that, small rigid acrylic sheets were placed on sensor surface before the application of the load in order to ensure good contact with sensor surface and load. Four measurements were performed for each sample.

3. RESULTS AND DISCUSSION

The initial electrical resistance of the soft resistive sensors was measured as very high resistance (non-conductive case) before any applied load. This indicates that sensing structures could also be utilized as flexible pressure switches within the e-textile applications. Figure 4 shows the electrical response of the both type of sensors.

As seen above figure 4, while type 1 becomes electrically conductive at the 80 kPa pressure level, type 2 becomes electrically conductive at 1,5 kPa pressure level. Thus, these pressure levels can be arranged as threshold for switch mechanism. The difference in pressure levels stems from the size of the holes in mesh fabric. Since conductive fabrics are separated from each other with mesh fabric, structures become conductive when the two conductive fabrics touch each other and larger holes in mesh fabric enables the structure to be conductive under the lighter pressure levels. This property of the sensor is useful in real applications since the pressure range of the applications is different from each other, i.e., type 2 sensor can be used as tactile sensor and type 1 sensor can be used where the higher forces needed such as foot pressure mapping. After the threshold levels, sensors' resistance for both types decrease up to the saturation level gradually. For the Type 1 sensor, working range of the sensor is between 80 kPa and 180 kPa and electrical resistance of the sensor does not change above this pressure level. However, change in resistance between the pressure level of 80 kPa and 140 kPa is much higher compared to rest of the pressure levels. Therefore, pressure sensitivity of the sensor is calculated for each region separately. The sensitivity (S) of pressure sensor can be calculated as $S=\Delta R/R_0/P$ where P represents the applied pressure, and ΔR and R_0 represent the change in resistance and initial resistance, respectively. For the Type 2 sensor, working range is found to be between 1,5 kPa and 50 Kpa. However, change in resistance between the pressure level of 1,5 and 10 kPa is much higher compared to rest of the pressure levels similar to previous case. Table 1 and Figure 5 show the working ranges of the sensors and related pressure sensitivities.

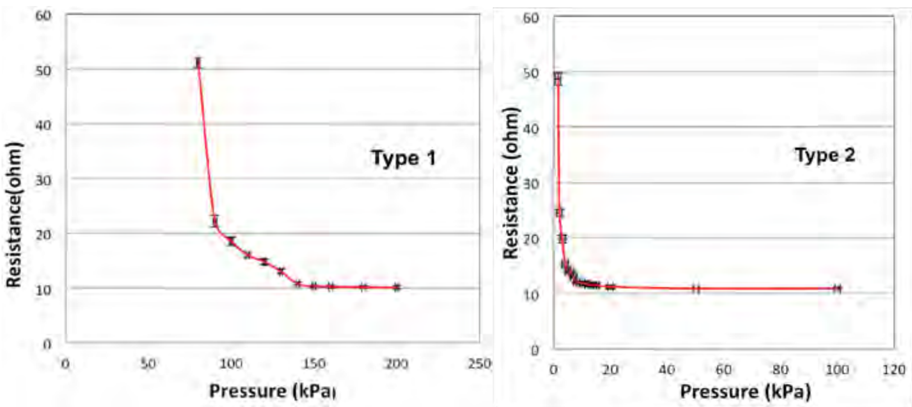

Figure 4. Electrical response of the sensors under applied pressure (a) Type 1 (b) Type 2

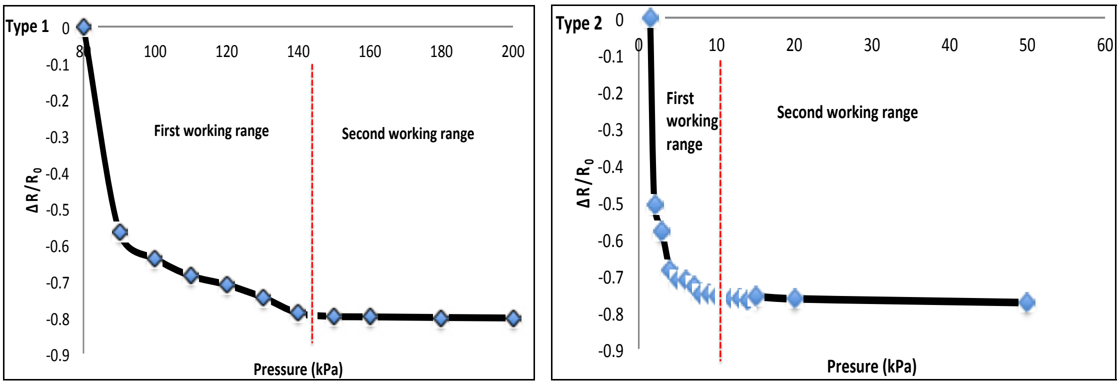

Figure 5. Normalized resistance values and working range of the sensors

Table 1. Working range and sensitivities of the sensors

Type 1 Sensor	**Range 1**	**Range 2**
Working range	80-140 (kPa)	140-180 (kPa)
Sensitivity	13x10^{-3}	1x10^{-3}
Type 2 Sensor	**Range 1**	**Range 2**
Working range	1,5-10 (kPa)	10-50 (kPa)
Sensitivity	75x10^{-3}	1x10^{-3}

As seen from the table 1, sensors with bigger mesh size (type 2) have higher sensitivity compared to smaller ones due to the significant change in electrical resistance value at lower pressure levels. After the first working range, sensitivity of the sensors decreases significantly for both types. However, level of decrease is lesser for type 1 sensor since smaller mesh size enables gradual contact between the top and bottom layer conductive fabrics through the its mesh structure. Both types of sensors can be considered highly sensitive sensors especially in their first working range due to the substantial decrease in their electrical resistance values. Capineri [28] reported highly sensitive fabric based resistive pressure sensors using steel and copper wires and sensors' sensitivity found to be 2.37 kPa^{-1} and 1.13 kPa^{-1} respectively. However, sensors' working range was very limited, i.e., up to the 4.55 kPa. In another study, a conductive fabric was placed between tooth-structured silicone molds for the construction of resistive pressure sensor and its sensitivity found to be 2,98x10^{-3} kPa^{-1} with the working range of 2000 kPa [27]. 3D spacer fabrics were also employed to produce resistive based pressure sensors and sensitivity values of these structures reached up to 50.31x10^{-3} kPa^{-1} sensitivity level [29]; thus, when the proposed sensors are compared with current works, both proposed sensors on this research work are found to be suitable for tactile sensing due to their high sensitivity values.

On the other hand, type 1 sensors have wider working range compared to type 2 due to the gradual contact between the conductive fabric layers. To demonstrate the application of the sensor in real environment, sensor was configured to pass current to a light-emitting diode (LED) under applied pressure as shown in figure 6. The LED remained lit as the soft sensor was pressed and turned off when it was not pressed.

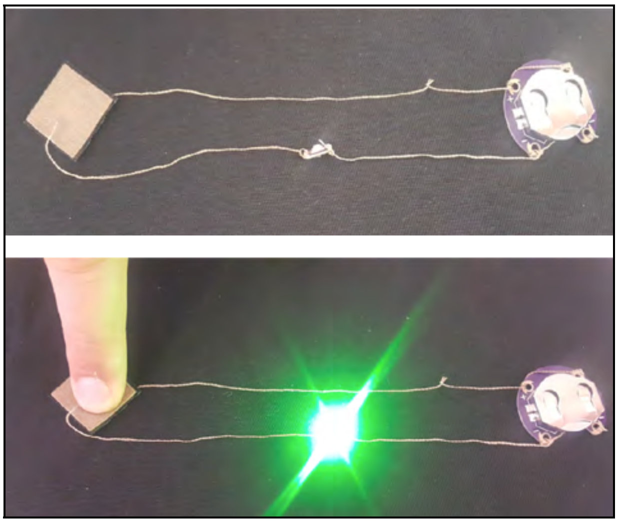

Figure 6. Application of the soft sensor in a developed circuitry

Herein, electrical circuitry consists of silver plated nylon yarn (conductive yarn), led, three-volt battery and its holder. Conductive yarn connects battery, led and soft sensor and it also serves as power transmission line. When there is no pressure on sensor surface, no electrical current flows therefore led does not light. As opposed to previous case, when sensor is pressed by finger current flows through the circuitry and led remains lit.

ACKNOWLEDGEMENT

The author would like to thank Dr. Aslı Tunçay Atalay for the sample preparation.

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