Design, development and analysis of a conductive fabric based flexible and stretchable strain sensor

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Abstract. This article presents the design, fabrication and characterisation of an elastomeric flexible and stretchable strain sensor using a variable resistance fabric. This provides a viable alternative to the microfluid and nanoparticle based flexible strain sensors involving complex fabrication techniques. A nylon-spandex based stretchable fabric serves as the sensing element which is in turn embedded in an elastomeric substrate. The fabricated sensor is experimentally characterised for determining the linearity, hysteresis, stretchability and gauge factor. The Finite Element Method based simulations to predict the operational force range of the sensor corresponding to its strain sensing range has been validated with the experimental results. These sensors have a wide range of potential applications in the constantly developing field of compliant robotics and mechanisms. In future works, these sensors will be utilized in the biomechanical analysis of human movements to track the various joint parameters.

1. Introduction

Flexible sensors [1], have an extensive demand nowadays due to their numerous applications in flexible health monitoring and surgical systems, wearable electronics, man-machine interaction systems, etc. With the rapid advances in the field of soft and compliant robotic systems, compact and lightweight sensors are extremely necessary to provide the valuable feedback to these systems. These bio mimetic robotic systems are often highly flexible and might also be used or worn by a human. These systems require a constant feedback of position, movements or even pressure. Conventional sensors and feedback devices like encoders, pressure sensors, etc. would make the system bulky and would ultimately compromise the wearability of these systems. This calls for the use of flexible and stretchable strain or pressure sensors which provide the necessary feedback yet do not hinder the natural motion of the wearer. These sensors are also much compact and lighter in weight as compared to the conventional sensors. Flexible strain and pressure sensors generally consist of a flexible substrate and a sensing element embedded in it. When used with a proper acquisition circuit, the sensing element provides meaningful electrical signals in response to the physical deformations of the sensor. These sensors can be categorised into mainly two types, capacitive type and Resistive type on the basis of their working principles.

1.1. State of the art

The field of wearable technology has been revolutionized by the development of a new type of strain sensors termed as “flexible strain sensor”. These sensors being highly flexible, can bend and stretch up to large extents, yet retain their repeatability over a large number of actuation cycles.
In literature stretchable strain sensors are broadly categorized into resistive based and capacitive based. These categories have dominated the area because of their ease of fabrication and soft materials compatibility. Seyedin et al. [2], gave a detailed review of various fabrication techniques involved in the development of flexible sensors. Capacitive. Atalay et. al [3], designed a stretchable conductive fabric based capacitive sensor for detection of human movements and exoskeletons. The sensor has been fabricated with two parallel knit fabric as electrodes and an elastomer in between acting as a dielectric. The sensor showed extremely low hysteresis with high linearity and 1.23 as its Gauge Factor. As an application of the developed sensor, the author has tracked finger motions by mounting the sensors on a reconstructed glove. Atalay [4], also developed a coplanar parallel plate capacitance based strain sensor with potential applications in tracking human joint angles. The sensor was fabricated with elastomer as substrate and interdigitated conductive fabric as electrodes pasted on it. The developed sensor showed a good resolution of 1.36 but a high response time of 50 ms. Totaro et al. [5], developed smart knee cap and anklet for detection of joint motion parameters. Each such smart garment was provided with three parallel plate capacitive sensors in the front and two at the back.

The smart garment could track the joint parameters upto a range of 30% strain. Bodini et al. [6], has developed a low cost force sensor for biomedical applications based on coplanar fringe capacitance sensing. A wafer of three polymeric layers with a polyamide PCB in the middle was used to fabricate the sensors. It was tested upto a force of 1N and it showed a hysteresis of 20 fF, sensitivity of 172 fF/N. Filippidou et al. [7], developed a low cost capacitive strain sensor using Graphene nanoparticles. The authors introduced a simple method to fabricate the sensor using a homogeneous suspension of Graphene in PDMS. The sensor showed linear behaviour upto 0.2% strain.

1.1.1. Resistive. Yamada et al. [8], developed a stretchable strain sensor capable of operating upto 280% strain. Carbon nanotubes in the form of single walls were used as the sensing element embedded on a stretchable PDMS substrate. The sensors showed good performance even in tracking intricate movements like human speech. Park et al. [9], developed a conductive micro fluid based stretchable resistive type strain sensor. The sensor was used to detect the ankle plantarflexion and dorsiflexion movements and provide a feedback to the controller of an ankle rehabilitation device. Yan et al. [10], designed a PDMS based sensory cable with an embedded microfluidic channel filled with Eutectic Gallium Indium liquid metal alloy and copper strand. Similar to the work of Park et al. the sensor works on the principle of change in resistance across the conductive fluid channel in response to the channel deformation due to strain. Gong et al. [11], developed a polyaniline PDMS based strain sensor having an extremely high gauge factor of 54 at a strain of 50%. The resistance of the sensors increases in response to the increasing strain due to the increase in the number of microcracks in the sensing material. Bae et al. [12], fabricated a graphene based transparent strain sensor using stamping and reactive ion etching techniques.

The sensor showed variations in piezoresistance with variations in strain upto 7%. The authors showed applications of such sensors in tracking finger motions. Tangsirinaruenart et al. [13], developed a conductive thread based stretchable strain sensor with a working range of 50% strain. Although the sensor shows good performance, the fabrication technique involves complex stitching processes which might not be repeatable without specific machinery. Cédric Cochrane et al. [14], fabricated a resistive type flexible strain sensor using conductive polymer coating technique. The sensor was made of a Styrene-Butadiene-Styrene as a polymer material and carbon black as a conductive filler material. The sensor exhibited a high gauge factor with a sensing range of 45% of strain. J. Wu et al. [15], developed a conductive fabric by oxidative polymerization process using nylon lycra as a stretchable component and polypyrrole as a sensing element. This fabric could sense upto a strain of 60%. This polypyrrole coated fabric showed non-linearity, low hysteresis and gauge factor of 3.5% at 20% strain.
1.2. Motivations and objectives
The orthodox semiconductor and metal foils based strain gauges have a low operation range (<5% strain) [16], hence not preferred for flexible electronics. While commercially available flexible and stretchable strain sensors are extremely expensive, the sensors developed in laboratory involve quite complex fabrication techniques and expensive equipments. In this article we present the development process of a flexible and stretchable strain sensor having an affordable fabrication process and requiring much less complex techniques. These flexible sensors have their applications mostly in tracking the different biomechanical parameters of human movements like joint angles or detecting gait events of heel strike, toe off, etc. As these applications involve repetitive tasks and flexible strain sensors generally have much limited number of cycles before failure, the conductive fabric based sensor presented in this article serves as a viable economic alternative. The sensor consists of a sensing element track embedded in a flexible elastomeric substrate. Unlike capacitive based strain sensors, the developed sensor does not involve the problem of sensor plate misalignment during fabrication as it involves only a single layer of conductive fabric which exhibits a change in the resistance along the track in response to strain. This article also presents a Finite Element Method based study to determine the operational force range of the sensor.

2. Design
The design of the sensing element of the sensor has been inspired from the design of conventional strain gauges. The sensory track has been designed with a uniform width of 5 mm all throughout. As seen in Fig. 2, the 378µm thick track of conductive fabric has been embedded at the middle of a 5mm thick elastomeric substrate. The sensor has been designed using a stretchable conductive fabric which exhibits a decrease in resistance in response to increasing strain [17]. This serves as the sole principle behind the sensory capability of the developed flexible strain sensor.

**Figure 1(a).** Front View of the sensor depicting dimensional details.  
**Figure 1(b).** Side View of the sensor  
**Figure 1(c).** Isometric view of the sensor showing silicone substrate and conductive fabric.
3. Fabrication

A commercially available stretchable conductive fabric, EeonTex™ LTT-SLPA from Eonyx Corp. has been used as a sensing element. This stretchable fabric is made up of 72% Nylon and 28% Spandex. As seen in Fig.2, it has a single bed knit structure. It is bi-directionally stretchable fabric having a proprietary conductive coating. This fabric has potential applications in development of strain and pressure sensors. It is commercially available as a 378 micro meter thick sheet. The proprietary coating can withstand a maximum of 30 wash cycles, after which it tends to exhibit no variation in resistance in response to strain. The sensory track has been laser cut from the sheet into the desired shape as seen in Fig. 3(a) and Fig. 3(b).

Ecoflex™ 00-50 from Smooth-On has been chosen as the hyper-elastic material to fabricate the elastomeric substrate. This RTV silicone can go upto a percentage of strain high enough to be used as a substrate in flexible and stretchable sensors. This silicone has a working time of 18 minutes and a curing time of 3 hours at 25°C. However the curing can be accelerated with heat treatment. The silicone substrate being hydrophobic provides a protective sheathing to the sensing element embedded in it as well as increases the operational strain range of the sensor. This material comes in two parts which have been mixed in 1:1 ratio by weight and stirred thoroughly for 2-3 minutes. As seen in Fig.4 the prepared mixture has been kept in the degassing chamber at a pressure of 29 inches of Hg for 3 minutes to remove any air bubble that might have got trapped during the stirring process.
As seen in Fig. 5(a), (b) and (c), the sensor has been fabricated using a three step molding process. A 3D printed mold has been used in the molding process which has been coated with a mold release spray, EASE RELEASE 200 from Smooth On. Firstly, the prepared silicone has been poured into the mold upto a layer height of 2.5 mm as in Fig. 5(a). Further it has been heat treated at a temperature of 40°C for 5 minutes in order to bring the silicone to a semi cured state. In the second step as seen in the Fig. 5(b), the laser cut sensing element has been carefully placed on the semi cured silicone layer using tweezers. The silicon-fabric assembly has been heat treated at a temperature of 40°C for 40 more minutes to fully cure this silicone. As in Fig.5(c), a silicone layer of 2.5 mm has been further poured over the previously cured silicone layer. The whole set up has been heat treated at 40°C for about an hour. The sensor, extracted from the mold can be seen in Fig. 5(d).

Figure 5(a). Molding Step 1  Figure 5(b). Molding Step 2  Figure 5(c). Molding Step 3

Figure 5(d). Fabricated Sensor after extraction from the mold

4. Testing
The fabricated sensor has been mounted on the test rig with the help of insulated gripping attachment on one end it has been connected to the load cell and on the other to a steel wire which is in turn pulled by a motor running in position control mode as seen in Fig. 6(a). In order to measure the change in
resistance across the sensor a voltage divider circuit consisting of a 10 mega Ohm standard resistance, 5V dc power supply and the sensor connected in series, has been used as seen in the Fig. 6(b). In order to track the stretch in the sensor, a LVDT has been attached to the movable gripping attachment.

![Custom made experimental Setup](image1)

**Figure 6(a).** Custom made experimental Setup

![Schematic representation of circuit utilised for measuring the resistance change across the sensor.](image2)

**Figure 6(b).** Schematic representation of circuit utilised for measuring the resistance change across the sensor.

The sensor has been stretched at a speed of 50mm/min with a step of 5mm in the loading cycle, upto a maximum strain of 71.42% corresponding to a stretching of 40mm. Stretching the sensor beyond that has shown no significant change in resistance across the sensor. The synchronized load cell and LVDT values have been recorded through a Data Acquisition System. Following that, the sensor has been unloaded at a speed of 50mm/min. Three such loading-unloading cycles have been performed.
5. Simulation

In order to design a flexible sensor using a silicone substrate, it is of utmost importance to predict the behaviour of the sensor before fabrication. In this article we present a FEA study in COMSOL Multiphysics to determine the maximum force corresponding to the maximum strain that can be reported by the sensor. For the purpose of the static simulation, the elastomeric substrate has been designed with the dimensions 56mm X 52mm X 5mm allowing a gripping area of 52mm X 4mm on the two opposite shorter sides as shown in Fig.7 (a). Ecoflex 00-50 being a hyperelastic material, exhibits non-linear stress strain characteristics and has a density of 1.07g/cc. So, as in [18], a 3rd order Yeoh model has been used to simulate the behaviour of the elastomeric substrate. As per literature, \(c_{10} = 1.9\times10^{-2}\) MPa, \(c_{20} = 9\times10^{-4}\) MPa and \(c_{30} = -4.75\times10^{-6}\) MPa have been used as the parameter values, considering the hyperelastic material to be incompressible. Two gripping attachments at the two shorter ends have been simulated using material properties of aluminium alloy having density 2.7g/cc, Poisson’s Ratio 0.32 and a Young’s Modulus of 6.89E04 MPa. A fixed boundary condition, having no linear or rotational degrees of freedom has been applied to the gripping attachment on one side of the sensor, while the other attachment is free to move.

![Figure 7(a). Boundary Conditions and applied Loads.](image1)

![Figure 7(b). Tetrahedral Meshing of the silicone substrate.](image2)

A parametric study has been conducted on the sensor, by varying the total load applied on the free end of the sensor in a step of 2N upto the load corresponding to the maximum strain sensing limit of the sensor. In order to tackle the large amount of deformation in the hyperelastic material, free tetrahedral elements have been chosen for meshing, using an element size of 1.5mm, based on the grid independence study as seen in Fig.7(b). A stretched form of the sensor in the simulation environment compared to the original form outlined in black, can be seen in Fig. 8(a).
6. Results and Discussions

To analyze the performance of a flexible and stretchable strain sensor, stretchability, linearity, gauge factor and hysteresis are important performance parameters to be determined. As seen in Fig. 9, the developed sensor using an elastomeric substrate shows hysteresis over the loading and unloading cycles which is mainly due to the viscoelastic nature of the substrate. A maximum of 9.86% hysteresis has been observed over the three loading-unloading cycles.

As seen in Fig. 10, the developed sensor can reliably sense up to a strain of 71.42%, as the sensor has been observed to retain the monotonicity in its behavior up to this level. Beyond this, the sensor loses its monotonicity and the sensory feedback is erroneous enough to interpret a finite value of strain. As in Fig. 10, the sensor has an operational force range up to 10.6 N corresponding to a maximum strain of 71.42%. It has been observed that the simulation results of the silicone substrate of
the sensor follow a similar trend as that of the experimental results and predict a maximum working force of 12.35 N for the elastomeric substrate of the sensor.

![Graph showing %Strain vs. Force](image1)

**Figure 10.** %Strain vs. Force plot of experimental data for the sensor and simulation data for the silicone substrate.

It has been observed that the resistance across the sensing element decreases uniformly in response to strain up to a maximum strain of 42%. In order to establish a linear sensing range a best fit line for the mean loading and unloading cycles has been shown in Fig. 9. The slope of this line can be interpreted as the Gauge Factor of the sensor. Gauge Factor of a sensor can be defined as the ratio of percentage change in resistance to the percentage strain. The developed sensor shows a Gauge Factor of 1.083 which is good enough for its potential applications.

![Graph showing %Strain in sensor vs. %Strain in conductive fabric](image2)

**Figure 11(a).** Tracing the sensing element track in ProAnalyst image analysis software.  
**Figure 11(b).** %Strain in sensor vs. %Strain in conductive fabric.
It is essential to investigate the actual strain in this sensing element due to the strain in the total sensor, so as to ensure that the conductive fabric operates within its working range. The sensory track has been traced from the images capture during experiments in an image analysis software, ProAnalyst, as in Fig. 11(a). The marker data has been exported to MATLAB and through a custom made code the lengths of the sensory track have been computed over the working range of the sensor. Fig. 11(b) shows a maximum strain of 41.64% corresponding to 71.42% strain in the sensor.

7. Conclusion
A flexible and stretchable strain sensor has been developed using a commercially available elastomer and a stretchable conductive fabric. The sensor has been developed using a simple fabrication technique and shows an operational strain range of 70% with a linear range of 42% and a gauge factor of 1.083. The sensor also shows a low hysteresis. These types of stretchable and flexible strain sensors would find their applications in areas of human joint-motion monitoring, facilitating sensing over a wide range of strain without hindering the flexibility in natural motion. Future works would include characterization of the conductive fabric which would enable an application specific design optimization.

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