Characterization of a new flexible pressure sensor for Body Sensor Networks

Sravan Salibindla #1, Brice Ripoche *2, Daniel T. H. Lai #3 , Simon Maas $4

Faculty Research Group in Telecommunications, Electronics, Photonics and Sensors, Victoria University, Australia
1 sravanreddy.salibindla@live.vu.edu.au
3 Daniel.Lai@vu.edu.au

* *Universit de Bourgogne*
Dijon,France
2 brice_ripoche@etu.u-bourgogne.fr

$ *Racesafe Australia*
4 simon.maas@racesafe.com.au

***Abstract*—Pressure sensors are generally used in body sensor networks to measure physical forces exerted by our limbs. Popular sensors include the force sensitive resistor and the piezoelectric sensors, both made of rigid semiconductor technology. However, the application of these sensors to human movement monitoring necessitates that these sensors be made flexible. This paper focuses on the design of flexible pressure sensors, in particular on the effect of electrode composition and thin film carbon infused conductive layers on a force sensitive resistor based pressure sensor. Fourteen pressure sensor designs with Velostat as a piezo resistive layer were developed with a variety of electrode materials i.e. silver, copper and tin. These sensors were characterized into three types, according to the properties of the conducting material placed with respect to insulating material in the pressure sensor. Our force versus resistance and deformation experiments reveal similar trends to popular semiconductor based force sensitive resistors (FSRs) i.e. Tekscan and Novel sensors. The best sensor design achieved a resistance range of 4000Ω over a force range of 0 to 20N. The design consisted of silver-nylon conducting thread stitched into a neoprene insulator layer. Tests demonstrated that the developed sensor was reliable and the performance was repeatable.**

***Index Terms*—Textile sensors, Wearable sensors, Velostat based sensor**

I. INTRODUCTION

About 90 percent of the human body is usually covered with clothes which make it feasible to use garments for collecting vital signal associated with health. Metrics of interest include body parameters such as breathing rate, body temperature, sweat content etc. If these garments are outfitted with sensors, they enable us to monitor the human body continuously without the requirement of specialized lab setups. Recently, there has been a considerable amount of work in the area of textiles sensor monitoring [1], [2], [3]. In addition to health, these wearable textile sensors can also be used for monitoring sports and other movement activities [4].

Textile pressure sensors are used in sports related applications for measuring forces applied by limbs. Recent work has demonstrated textile pressure sensors for biomechanics measurements [5], however the parameters involved in the sensor design have not been reported systematically. In this paper, we investigate the design of new flexible pressure sensors based on piezoresistive materials and conductive textiles. We report on the designs of 14 different textile pressure sensors and comment on the factors which could be used to improve textile sensor range and sensitivity. These designs adopt similar principles to the silicon based Force Sensitive Resistor (FSR), but use more flexible materials in the design. The sensors can be used in applications of biomechanics, human motion analysis, and monitoring of limb strength.

The paper is organized as follows; section 2 describes the various sensor design, followed by section 3 that gives the information on the experiments done, then section 4 outlines the results and the discussion follows.

II. SENSOR DESIGN

Sensors were designed using three basic materials as shown in figure 1 where the middle layer consists of a piezoresistive plastic sheet (Velostat) sandwiched between two conducting layers. Velostat is a carbon thin (4mm) infused plastic (polyolefin) that has a high resistivity ($< 500\Omega$ per cm). The resistance of Velostat changes when pressure is applied. The conducting layers act as electrodes and consist of either conducting fabric or conducting thread. The sensor package is then completed with insulating tape i.e. duct tape to avoid short circuits between the two conducting layers. In this design, the change in resistance of the piezoresistive Velostat is investigated with respect to applied force and deformation. Based on this construct, we developed three basic sensor designs, namely Types I, II and III as follows.

A. Type I Sensors

In the first design, we utilized a $16cm^2$ Velostat layer sandwiched between two layers of $10cm^2$ conducting fabric made from medical grade elastic fiber (76% Ag plated and

Fig. 1. Flexible sensor assembly from left to right showing the electrode layers, conductive plastic layer and the final packaging.

24% Nylon). Duct tape was used as a general adhesive and package. Conducting copper wires were connected to the conducting fabric to allow ease of connectivity to external measurement devices.

B. Type II Sensors

In the second kind of sensor, we maintained $16cm^2$ of velostat as the middle layer and replaced the conducting fabric with conducting thread composed of the same medical grade elastic fiber. The conducting thread acted as the electrodes and were attached to the duct tape package. Care was taken to ensure that the electrodes did not form a short circuit. Various sensors were designed by altering the number of Velostat layers, composition of the conducting thread, electrode size and electrode shape as depicted in Table 6.

C. Type III Sensors

In the third type of sensor, the size of the Velostat was maintained at $16cm^2$. The electrodes were made by stitching conductive thread into neoprene strips and constructing the sensor package as depicted in Fig 2. Conducting copper wires were connected to the conducting threads for application and testing of the sensor.

Fig. 2. Type III sensor.

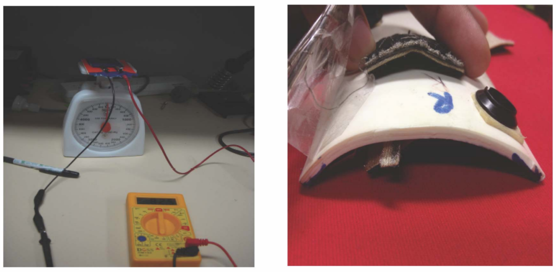

Fig. 3. Experimental setup for sensor characterization and deformation tests.

III. Experimental Setup

A. Resistance Characterization

The experiments are done by using a calibrated weighing platform and a multimeter for measuring the ohmic resistance between the electrodes of the sensor. A circular block was used to apply a uniform force perpendicular to the surface of the sensor. The applied force was varied between 0-25N, and the readings taken from the weighing platform. The experiments were repeated three times and averages were reported for each of the fourteen sensor designs.

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B. Deformation Reliability

In this experiment, each sensor is deformed along the length and widths simultaneously to a maximum bend of 30 degrees (Fig 3). The change in resistance was measured at various deformation levels. This process was repeated by varying the period between two deformation cycles from 30-120 seconds.

IV. Results

Figure 4 shows the average results of experiment III-A for all fourteen sensors. It can be seen that maximum resistance changes for type I sensors was approximately 300 Ω and 900 Ω for type II. Type III sensors had a large range, with a maximum of 4000 Ω. Type I and II sensors were less responsive to forces larger than 20N, as seen by the decreased resistance change at higher applied forces. In addition, sensors designed with thread electrodes laid out in a square fashion resulted in minimum resistance change as seen in Figure 4.

Figure 5 shows the results for the second experiment III-B for a type 1 sensor (conductive10sq.cm fabric), two type II sensors (thread6cmsilversemicircleconnectedthrufabric sensor, thread12cmsilver2spiralconnectedthrufabric sensor) and a type III sensor (Threadofsilverstitchedthuneoprene sensor). The graphs show the deformation trends along the width and lengths of the sensors. The resistance change for type I

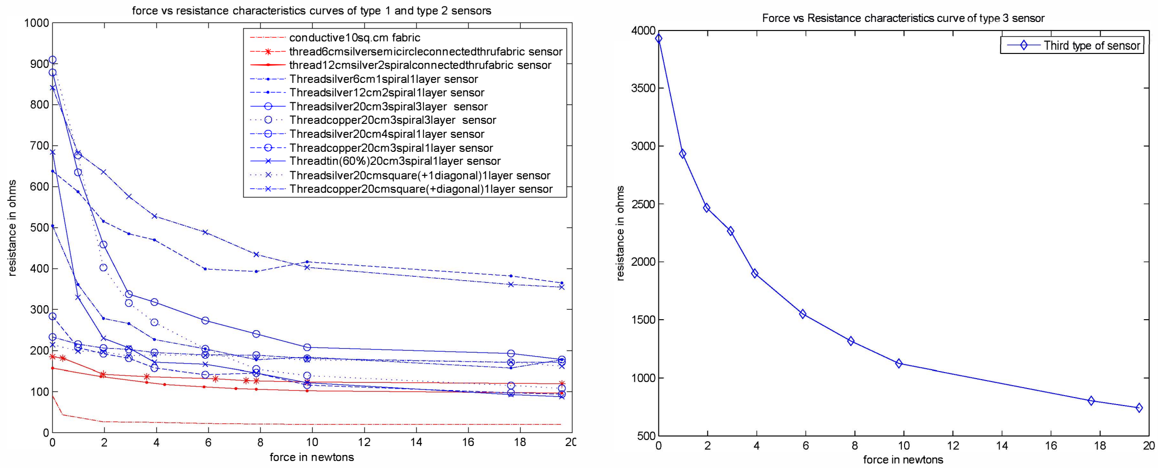

Fig. 4. Left: Resistance characteristic curves of type I and II sensor. Right: Resistance characteristic of a type III sensor.

under deformation were within the range 400-600 Ω over six deformation cycles. The range was consistent over the width, but decreased slightly when deformed along the length of the sensor. Both type II sensors had a resistance range change of 200 Ω, albeit different actual resistances i.e. sensor with 12cm thread electrodes had double the resistance compared to the sensor with 6cm thread electrode.

V. Discussion

In this work, we have constructed several flexible sensors for measuring forces based on the piezoresistive effects of the carbon infused plastic. From figure 4, we observed that the change in resistance was inversely proportional to the increase in force. The trends observed were similar to standard commercially available force sensitive resistors (FSRs). Increases in the number of layers of Velostat increased the resistance range and also the sensitivity of the sensor. This can be observed for example when comparing both the *Threadcopper20cm3spiral3layer* and *Threadcopper20cm3spiral1layer* sensors.

Electrode composition and configurations influenced sensor sensitivity (change in resistance per unit force). It was observed that square conductive fabric electrodes resulted in the poorest sensitivity (Figure 4), i.e. Type I sensor. For type II sensors, it was found that thread electrodes in a spiral shape produced sensors with the best sensitivity. In our experiments, we found the highest sensitivity achieved by using tin (60%) wire electrodes in a spiral configuration. Type III sensors with neoprene embedded thread electrodes appeared to have the largest sensitivity overall, with a resistance range of approximately 4000 Ω.

The geometry of the conducting electrodes on the Velostat effected the range and sensitivity. For example, the spiral electrodes (Threadcopper20cm3spiral1layer, Threadsilver20cm4spiral1layer) had a higher resistance change compared with the respective square electrodes (Threadcopper20cmsquare(+diagonal)1layer, Threadsilver20cmsquare(+1diagonal)1layer). The length of the spiral electrodes influenced the maximum resistance, where doubling the length of the same electrode configuration also doubled the resistance range i.e. comparing Threadsilver12cm2spiral1layer with Threadsilver6cm1spiral1layer.

Comparisons between type I and type II sensors revealed that a smaller density of electrodes i.e. thread compared to fabric, resulted in a higher resistance change. However increasing the length of the electrodes in contact with the piezoresistive surface (Velostat) increased the maximum resistance, which would be expected as more electrode material was in contact with the Velostat. These two opposing observations led us to conjecture that the resistance changes in the sensor under pressure was due to the manner in which the electrodes made contact with the Velostat. This thought was further reinforced when observing type III sensors which had a soft, elastic neoprene electrode base and more room for the electrodes to make contact. The type III sensor had the highest resistance range (figure 5). If this was true, then the performance of these sensors was more dependent on the electrode construction rather than the piezoresistive properties of the carbon infused plastic. It also suggests that further attention should be paid to the electrode configuration to achieve better sensitivity.

Future work will need to investigate the findings above in detail. In particular, a consistent manufacturing process that was simple and reliable is required to develop better prototypes. Our preliminary investigations have revealed that it is possible to design self made pressure sensors that are cheap, soft and flexible. The sensors have potential of improving the wearability of body sensor networks currently being deployed in various biomechanics and health applications.

VI. Conclusion and Future Work

Different sensors have been designed and categorized based on the force sensitive resistor principle. The effect of the number of piezoresistive layers, electrode configurations, electrode composition and packaging were investigated. It was found that electrode configuration and composition affected the sensor performance the most. Future work will look at new electrode designs and verifying their importance in sensor performance.

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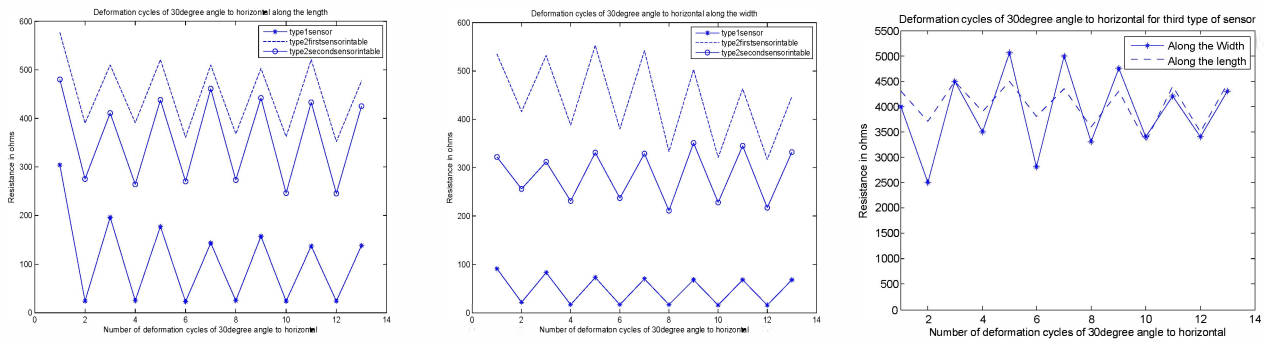

Fig. 5. Deformation test results for type I, II and III sensors.

Type	Name	Velostat (cm^2)	Sensor (cm^2)	Velostat layers	composition	Size of conductor layer	geometry	Number of spirals	Type of Connection to conductor
I	conductive10sq.cm fabric	16	25	1	Silver and lyca	10cm^2	Square sheet		Silver and lyca fabric
II	thread6cmsilversemicircleconnectedthrufabric sensor	16	25	1	Silver	6cm	Semicircle thread		Silver and lyca fabric
II	thread12cmsilver2spiralconnectedthrufabric sensor	16	25	1	silver	12cm	Spiral thread	2	Silver and lyca fabric
II	Threadsilver6cm1spiral1layer sensor	16	25	1	silver	6cm	Spiral thread	1	Copper
II	Threadsilver12cm2spiral1layer sensor	16	25	1	silver	12cm	Spiral thread	2	Copper
II	Threadsilver20cm3spiral3layer sensor	16	25	3	silver	20cm	Spiral thread	3	Copper
II	Threadcopper20cm3spiral3layer sensor	16	25	3	Copper	20cm	Spiral thread	3	Copper
II	Threadsilver20cm4spiral1layer sensor	16	25	1	silver	20cm	Spiral thread	4	Copper
II	Threadcopper20cm3spiral1layer sensor	16	25	1	Copper	20cm	Spiral thread	3	Copper
II	Threadtin(60%)20cm3spiral1layer sensor	16	25	1	Tin(60%)	20cm	Spiral thread	3	Copper
II	Threadsilver20cmsquare(+1diagonal)1layer sensor	16	25	1	silver	20cm	Square(+diagonal)		Copper
II	Threadcopper20cmsquare(+diagonal)1layer sensor	16	25	1	copper	20cm	Square(+diagonal)		Copper
III	Threadofsilverstitchedthuneoprene sensor	16	25	1	silver	20cm	Spiral thru neoprene	3	Copper

Fig. 6. Dimensions, electrode and piezoresistive layer properties of the 14 designed sensors.