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Screen printed capacitive free-standing cantilever beams used as a motion detector for wearable sensors

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Abstract

This paper reports the screen printing of free-standing cantilever beams on to fabric, for use as motion detectors. Such low cost motion detectors could be used in clothing as activity monitors to indicate if the wearer is unconscious in safety critical applications, e.g. a fireman in a building. We have fabricated capacitive free-standing cantilevers by screen printing sacrificial and structural materials onto a fabric substrate. In this paper, these devices are used as motion detectors which are mounted and tested on a human forearm alongside a commercial accelerometer, for comparison. The results show the feasibility of using a fabric based cantilever to indicate that the wearer is moving.

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Keywords: smart fabrics, low temperature sacrificial technology, motion detector, screen printing

1. Introduction

Smart fabrics have been widely researched [1-4] and offer electronic functionality (e.g. sensing and actuation) integrated within a garment. Typically, the electronic functionality is knitted or woven into the fabric structure. Screen printing is an attractive alternative solution because it offers significantly more design freedom and placement capability on fabrics compared with weaving and knitting based methods. Screen printing uses materials in a paste from which are printed through a pre-patterned screen. The pattern on the screen defines where the paste is deposited on the fabric. Therefore, the printing approach has no need to follow the yarn structure of the fabric. In addition, printing is widely used in industry for creating colour artwork on fabrics and is suitable for mass production.

Piezoelectric, piezoresistive and capacitive sensing elements can be used for detecting deformation or bending of a fabric and therefore motion of a human body on which the textile is worn as clothing [5-7]. By using sacrificial technology, a capacitive sensing element can be fabricated. This provides a simpler printing structure for motion detectors compared with piezoelectric and piezoresistive sensing as it only requires conductive, structural, and sacrificial layers. In addition, it does not require the harmful lead present in PZT, the predominant piezoelectric material. Capacitive sensing in smart fabric applications has been previously reported. *M. Sergio et.al.* [8] proposed a capacitive sensing element on fabric; changing the capacitance between rows and columns of conductive fibres patterned onto two opposite sides of an elastic synthetic foam. When the inner dielectric layer is compressed, the capacitance between a given row and a column increases. The problem is the neighbouring capacitor's charge

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injection which causes spurious injection of charge into the input of the readout circuit. *C. Merritt et.al.* [9] demonstrated a textile based capacitive sensor for respiration monitoring. This sensor was made by screen printing interconnections on two fabric strips and stitching them to a rubber elastic strip to form a belt. The capacitance change was caused by stretching the belt thereby changing the contact area. The main problems of this sensor were that the friction between the moving layers causes layers to rub together thereby restricting smooth operation. We report a motion detector which is directly screen printed on to fabric and offering a simple design and structure, small size, ease of fabrication, and the possibility of creating devices on a variety of substrates.

Previous studies at the University of Southampton [10] have successfully demonstrated cantilevers on fabric using a low temperature thermally removable sacrificial material. The material used is Trimethylolthane (TME) which is a plastic crystalline material which begins to sublime at a relatively low temperature (83 °C) and is fully removed at 160 °C. These temperatures are compatible with most fabrics and the process is well suited to fabricating three-dimensional structures including air spacer layers on fabrics. An electrically insulating interface paste, Fabink-UV-IF1, supplied from Fabinks Ltd., was printed firstly onto the fabric to achieve a smooth platform for subsequent layer printing. Then, a silver conductive paste was printed on the interface layer and cured at 125°C for 5 minutes to form the bottom electrode. Sacrificial paste was then printed and dried at 80 °C for 10 minutes. Next, the structural layer, EFV4/4965 was printed and cured under UV radiation for 60 seconds. Finally, Johnson Matthey S-20 was printed on top of the sacrificial layer to form the top conductive layer. For the sacrificial layer removal process, the samples were placed in an oven at 160 °C for 30 min. The dimensions of four sensors are shown in Table 1.

Table 1 Dimensions of motion detectors

Sample	1	2	3	4
Beam (mm)	9×10	12×10	15×10	18×10
Electrode (mm)	8×8	11×8	14×8	17×8

After the removal process, cantilevers were completely released from the substrate and the resonant frequencies of the four samples were tested by a shaker rig. Further details of this test are given in [10]. The capacitances were measured using a *Wayne Kerr 4350 LCR* meter and the frequencies and capacitances are shown in Table 2.

Table 2 Static capacitances of four sensors

Sample	1	2	3	4
Measured value (pF)	3.94	6.02	6.29	7.59
Experimental resonant frequency (Hz)	760	410	280	215
Modelling resonant frequency (Hz)	780	440	280	200

Since the capacitance of each cantilever is very small (~3-8 pF), the challenge for accurate capacitance measurement is the additional parasitic capacitance introduced by the connection wires. This capacitance is normally several orders of magnitude larger than the capacitor being measured. *J. de Rocha et.al.* [11] reported a circuit that was able to reduce the parasitic effect of wires. This circuit for detecting a change in capacitance is shown in Fig 1.

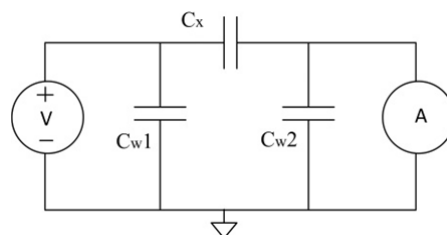


Fig 1 Schematic diagram of capacitance measurement [11]

As C_w1 is in parallel with the voltage source, its current is not measured by the ammeter. However, as C_w2 is in parallel with the ammeter and the impedance of the ammeter is very small, the current through C_w2 is zero. Therefore, current through C_x is measured by the ammeter directly and is only proportional to the v and ω . Therefore, the ammeter only measures the current passing through the motion detector C_x and this current is given by:

$$i_s = v\omega C_x \quad (1)$$

Where v and ω are the voltage and angular frequency of the voltage source and C_x is the capacitance to be measured. C_w1 and C_w2 are the parasitic capacitance of the wires.

2. Circuit design and test

2.1. Circuit setup

To achieve the capacitance measurement circuit shown in Fig 1, the voltage source and ammeter are replaced by a signal generator and a current-to-voltage converter respectively. A *TTi TGA1241* signal generator ($f=100\text{ kHz}$ and $V_{pp}=3.8V$) replaces the voltage source and the current-to-voltage converter is a transimpedance amplifier as shown in Fig 2.

The screen printed capacitive sensor is connected between the signal generator and the transimpedance amplifier followed by a full wave rectifier. A three-stage low pass filter removes high frequency noise from the signal generator. Finally, a non-inverting op-amp amplifies the voltage signal.

2.2. Sensor mounting and testing

Four motion detectors were individually mounted onto the forearm of the participant and tested separately. For comparison purposes, a commercial accelerometer (*MicroStrain G-link*), was mounted alongside the printed motion detector. The mounting position and motion detectors are shown in Fig 3. Data from the printed motion sensors and the *G-link* accelerometer were recorded for five seconds with the participant’s forearm moving up and down in front of their body with a motion distance of ~ 15 cm.

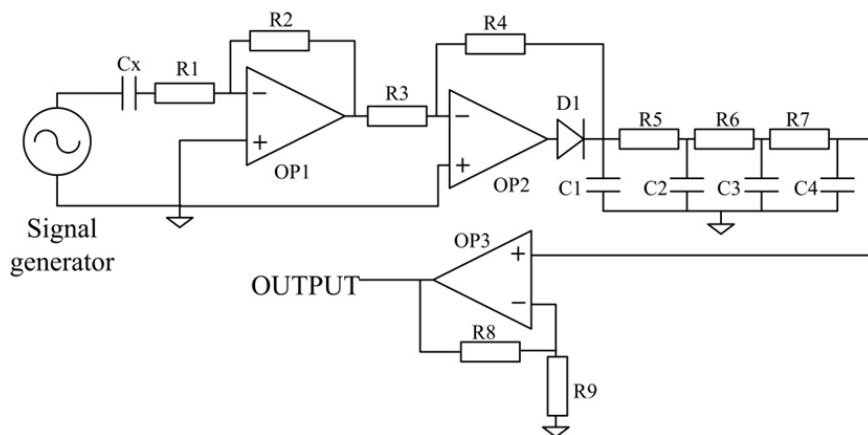


Fig 2 Circuit diagram of the readout circuit

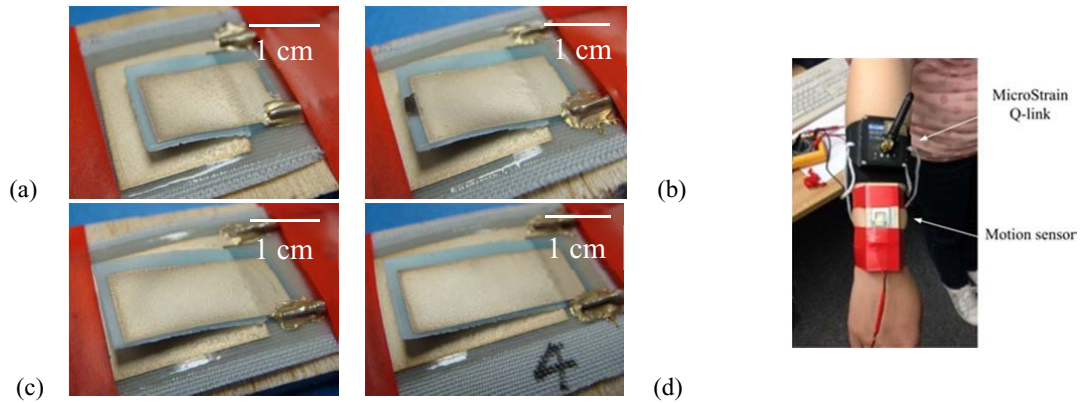


Fig 3 Screen printed motion sensor samples: (a) One (L : 9 mm); (b) Two (L : 12 mm); (c) Three (L : 15 mm); (d) Four (L : 18 mm) and mounting positions of sensors

3. Test results

The results presented in Fig 4 show that the capacitive motion detectors have a similar response to the *G-link* accelerometer when the forearm is moving. There is small amount of noise on the samples with lower capacitance, especially sample one. The larger capacitance samples (samples three and four) have lower noise. Fig 4(d) shows the best response because it has the lowest mechanical resonant frequency of the four samples (215 Hz). It has the best motion response of the sensors tested because it is relatively close to the human movement frequency.

4. Conclusions

This research has demonstrated the feasibility of using screen printed capacitive cantilever structures as motion detectors. The test results show that the motion detectors and the instrumentation amplifier circuit are capable of detecting human motion. In addition, it is shown that fully screen printed motion detectors have a similar motion response to the commercial accelerometer tested. However, due to the connection wires, a small amount of parasitic capacitance is introduced into the circuit causing noise in the detection signal.

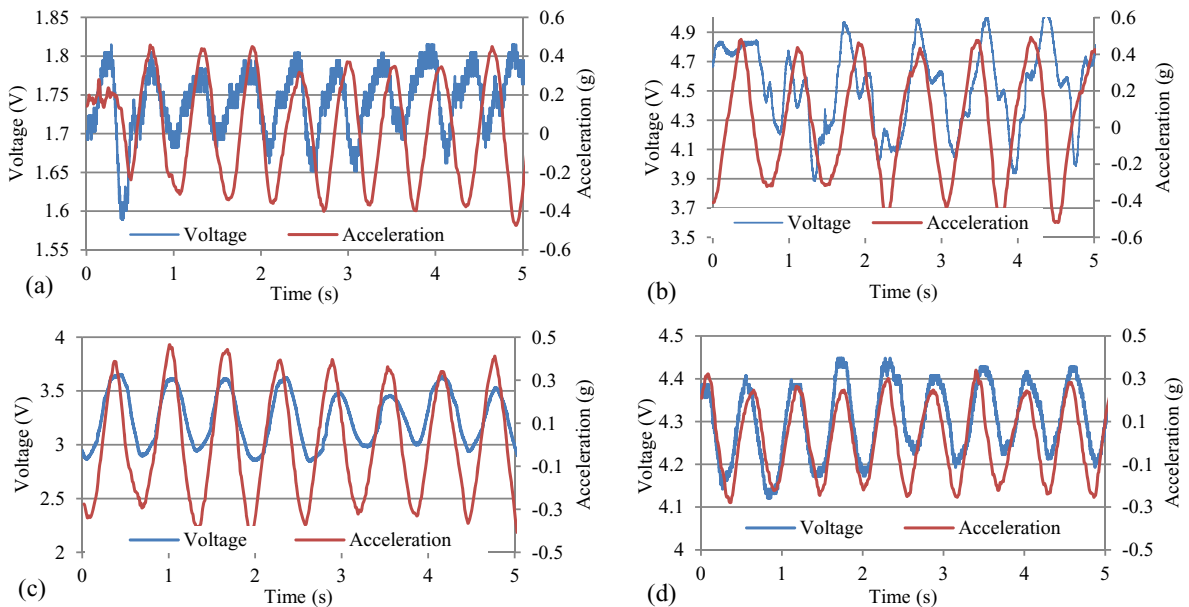


Fig 4 Comparison between the printed motion detector and the *G-link* accelerometer : (a) sensor one; (b) sensor two; (c) sensor three; (d) sensor four

This printing approach to motion sensing has the advantages of being lightweight, comfortable and unobtrusive for the wearer. This method also provides a simple fabrication procedure which uses a straightforward structural design to achieve motion detection. The simplicity of the fabrication procedure means that these sensors can be easily integrated into existing safety clothing or other garments produced by anyone from industrial printing companies to small print shops using the same methods as t-shirt printing. Finally, electronic circuit boards could be printed on the fabric alongside the motion detectors to form a complete printed sensor system on a garment using the processes developed in this study.

Future work will focus on reducing the size of the instrumentation circuit and replacing the signal generator with an on-chip oscillator to reduce the length of the wiring and thus further reduce the parasitic capacitance and noise in the system.

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