Capacitive wearable tactile sensor based on smart textile substrate with carbon black/silicone rubber composite dielectric

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Capacitive wearable tactile sensor based on smart textile substrate with carbon black/silicone rubber composite dielectric

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Abstract
To achieve the wearable comfort of electronic skin (e-skin), a capacitive sensor printed on a flexible textile substrate with a carbon black (CB)/silicone rubber (SR) composite dielectric was demonstrated in this paper. Organo-silicone conductive silver adhesive serves as a flexible electrodes/shielding layer. The structure design, sensing mechanism and the influence of the conductive filler content and temperature variations on the sensor performance were investigated. The proposed device can effectively enhance the flexibility and comfort of wearing the device as the sensing element has achieved a sensitivity of 0.02536%/KPa, a hysteresis error of 5.6%, and a dynamic response time of ~89 ms at the range of 0–700 KPa. The drift induced by temperature variations has been calibrated by presenting the temperature compensation model. The research on the time–space distribution of plantar pressure information and the experiment of the manipulator soft-grasping were implemented with the introduced device, and the experimental results indicate that the capacitive flexible textile tactile sensor has good stability and tactile perception capacity. This study provides a good candidate for wearable artificial skin.

Keywords: e-textile, capacitive fabric sensor, wearable, artificial skin, plantar pressure distribution, soft-grasping

(Some figures may appear in colour only in the online journal)
Electronic textiles (e-textile) including various electronic elements such as tactile sensors [8, 9], wearable electronics [10], and textile antennas [11] have attracted considerable interest with the development of advanced flexible and wearable devices [12]. Cost-effective manufacturing makes it attractive for the development of simple and low-cost systems that are effective for the wearable pressure sensors. Textile-based tactile sensors, in particular, have been widely explored for use in the sitting posture classification [13], health monitoring [14, 15], and gait analysis [16] due to the flexibility and integrability into clothes.

In this work, we present a novel design for a capacitive flexible textile tactile sensor with a carbon black (CB)/silicone rubber (SR) composite dielectric based on a screen printing technique. Textiles are utilized as flexible substrates, and thus the flexibility and wearing comfort of the device can be greatly enhanced. The remainder of the paper is organized as follows: the structure design, sensitive mechanism, and fabrication procedure of the sensor are described in section 2. Section 3 shows the experiment setup, and illustrates the physical and electrical characteristics of the fabric sensor, for example, its range, sensitivity, repeatability, linearity, hysteresis, and dynamic response. Moreover, the temperature compensation algorithm is introduced to compensate drift induced by temperature variations. Section 4 reports the application of the fabric sensor in plantar pressure measurement and soft-grasping. Finally the conclusion and future scope of this work are given in section 5.

2. Sensor design

2.1. Sensor architecture

Figure 1(a) shows the structure of the capacitive textile tactile sensor. Each textile sensing element consists of a basic multi-layer structure, forming a parallel-plate capacitor. The upper and lower electrodes are made of conductive rubber, and both sides of the flexible electrodes cover silicone rubber for insulating purpose. CB filled SR is used as a composite elastic dielectric to gain the effective dielectric constant. Therefore, the sensing range can be adjusted by changing the conductive filler content. It has distinctness meaning in spreading the area of application for artificial skin.

To achieve the capability of ultra-flexible and wearing comfort, the single-ended capacitive tactile sensor is printed on a flexible textile substrate. The flexible upper electrode works as a common ground plane that protects the sensor from electromagnetic interferences. Meanwhile, a shielding layer is adhered to the lower surface of flexible fabric to improve the anti-interference. Additional layers of silicone rubber are arranged covering both sides of the textile tactile cell protecting a protection function.

A magnified schematic of the mechanism is shown in figure 1(b). The basic sensing mechanism is equivalent to a parallel-plate capacitor in which the dielectric deforms when pressure is applied. The output capacitance \( C \) can be theoretically calculated by the following equation:

\[
C = \varepsilon_0 \cdot \varepsilon_e \cdot \frac{A}{d}
\]

Where \( \varepsilon_0 \) is the vacuum electric constant (8.854 187 817 \times 10^{-12} \text{ F m}^{-1}), \( \varepsilon_e \) is the effective dielectric constant of the composite dielectric which the value is determined by the conductive filler content and the deformation of the dielectric, \( d \) and \( A \) are the thickness of the dielectric layer and the effective area of the parallel plate electrodes, respectively.

The high dielectric constant of the CB/SR composites can be interpreted by the Kirkpatrick and Zallen statistic percolation model [17], which is used to predict the electrical properties of a percolation system with non-interacting randomly dispersed fillers. The value of the effective dielectric constant \( \varepsilon_e \) can be obtained as [18],

\[
\varepsilon_e = \varepsilon_0 (1 - f)^{-s} \varepsilon_c > f
\]

Where \( f, f_c \) and \( \varepsilon_0 \) are the filling factor, the percolation threshold, and the conductivities of the dielectric phases, respectively. The characterizing exponent \( s \) is assumed to be universal for a fixed system dimensionality, i.e. \( s = 0.7 \) for


According to the percolation theory, the high dielectric constant can only be obtained at filler loadings very close to the threshold.

From equations (1) and (2), the thickness of the dielectric layer $d$ decreases and the effective dielectric constant $\varepsilon_e$ increases accordingly, which is caused by the mechanical deformation of the CB/SR composite under external loads and results in an increase in the output capacitance. It is worth noting that the synergistic effect offers a high tactile sensitivity. The influence of carbon black content on the performance of the fabric pressure-sensitive element is investigated in the following paragraphs to obtain a higher sensitivity.

### 2.2. Sensor fabrication

The fabrication procedure of the device was explained in figure 2. A PP non-woven fabric (Huahao Non-woven Co., Ltd, Guangzhou) and YC-02 organo-silicone conductive silver adhesive (Nanjing Xilite Adhesive Co., Ltd, Nanjing) were selected as the flexible substrate and electrode/shield layer, respectively. Carbon black (CB3100, SPC Chemical Company, Sweden) filled with silicon rubber (GD401, Zhonghao Chenguang Co., Ltd, Zigong), and ultrasonic dispersion (FS-150, Shanghai Shengxi Co., Ltd, Shanghai) for an hour and degassed in a vacuum chamber (DZF-6021, Shanghai Suopu Instrument Co., Ltd, Shanghai). The prepared CB/SR mixture was introduced to the mold and cured at room temperature. The cured composite was detached from the mold and used for the dielectric layer. YC-02 organo-silicone conductive silver adhesive, remains highly flexible, stretchable and conductive after curing is complete, and was deposited and patterned on the mold using a shadow mask to create the electrode/shield layers for the sensing elements. The thickness of the dielectric and electrodes are 0.5 mm and 0.2 mm, respectively. The sensor unit was assembled by bonding each layer using a thin layer (<10 $\mu$m) of silicon rubber as an adhesive. Compared with a conventional fabrication process, screen printing offers the advantages of geometric design flexibility and the ability to simultaneously print multiple devices of the same or different designs [19].

![Figure 3. E-textile tactile sensor: (a) textile pressure sensing cell. (b) Attached to pen surface. (c) Integrated into a sock. (d) Bend. (e) Stretch. (f) Twist.](image)

Figure 3 is a photo of the e-textile tactile sensing. Since the device was fabricated by a textile-based flexible substrate and using a screen printing technique, the thickness of the sensing element can be easily reduced. Similarly, flexible and wearable comfort performances were improved. It is also convenient to sew into clothing without compromising the comfort of the wearer (see figure 3(b)).

As is shown in figures 3(d)–(f), the capacitive textile tactile sensor can withstand large mechanical deformations such as bending, stretching, and twist, etc. There is no noticeable crack formation or delamination during the cyclic mechanical deformation.

### 3. Experiments and discussion

#### 3.1. Experiment Setup

Figure 4 depicts the experiment setup used for applying a material testing machine and acquiring data during the sensor characterization. The whole system, comprising the translation stages, the load cell, and the capacitance acquisition board, was connected to a PC. A graphical user interface was implemented to acquire force and capacitance measurements simultaneously, and to control linear translation stages. The measurement was conducted by applying force on the sensor through the force gauge actuated by the $z$-axis of the moving stage. When the force gauge made contact with the fabric tactile sensor, the dielectric layer of the sensor was compressed. The distance between two parallel electrodes and the effective dielectric constant was changed and induced the change of the measured capacitance. The applied force and output capacitance can be measured by the force gauge with force resolution of 0.1 N (LS-WD-100, Shenzhen Lisen Electrical Technology Co., Ltd. Shenzhen) and the capacitance to digital converter AD7147-1, respectively.

Capacitance measurements were performed by means of custom electronics. Each capacitive signal was acquired by a 16-bit capacitance-to-digital converter (CDC) (AD7147-1, Analog Devices Inc., Norwood, MA, USA). The input dynamics of the CDC is 16 pF, which is fully used during sensor
characterization, and the active AC shield can effectively eliminate the parasitic capacitance between the CIN and the ground [20, 21]. The CDC is able to provide twelve measurements of capacitance and send them using I2C serial bus communication, through a digital line. In order to minimize the influence of parasitic capacitances (due to wires, connections, etc), the device was connected to the electronic board by means of shielded cables. The common ground plate and the shielding layer are connected to the GND and CINx (x = 0, 1, 2… 184) of AD7147-1, respectively.

The system block diagram was described in figure 5, and the capacitance-sensitive data was acquired by means of a high performance and low power microprocessor (CC2530, Texas Instruments Inc., Dallas, Texas, USA) and sent wirelessly to the upper computer. A software GUI written in LabVIEW was used to plot the data and distribution characteristics of the pressure in real time.

3.2. Evaluation of sensor performance

In this study, five mixing ratios, i.e. 0 wt.%., 4 wt.%, 6 wt.%., 8 wt.%, and 10 wt.%, of the CB/SR were prepared for the composite dielectric layer. In each mixing ratio, the output capacitance was measured under pressures varying from 0 KPa to 700 KPa. The measurement results of the different capacitance ranges are shown in figure 6. The normalized pressure-capacitance curves for different dielectrics indicate the mixing ratio of 6 wt.% possesses higher sensitivity (the initial capacitance $C_0$ is $\sim$4.3748 pF) and thus is chosen as the dielectric of the capacitive pressure sensor.

Figure 7 revealed the characteristics of the textile sensor in terms of measurement range, sensitivity, repeatability, and linearity. The sensitivity of the textile sensor was calculated as the slope of the normalized capacitance variation in function of the force, in different force ranges. The measurement range and sensitivity depends on the conductive filler content and the thickness of the composite dielectric. As shown in figure 7, the sensitivity of the sensor was about 0.02536%/KPa, and the linearity of the measurement response was shown by the $R^2$-squared value, i.e. 0.9981. The relationship between the output capacitance and pressure was expressed in equation (3).
Where $C$, $C_0$ and $P$ are the output capacitance, the initial capacitance and the loading pressure, respectively.

To evaluate the hysteresis properties of the sensor, some measures have been carried out by increasing and decreasing the applied force. Defining the hysteresis error as the maximum difference between the output values of the sensor obtained for the same input value, and the maximum error is 5.6% (see figure 8).

A pulsed contact pressure (of $\sim$230 KPa) in the frequency range of 0.1 Hz to 5 Hz has been applied to the sensor surface to analyze the dynamic response time ($\sim$89 ms). The response time, generally, is influenced by the viscosity of the CB/SR composite. As shown in figure 9, both the input stimulus and the output capacitance were recorded. The capacitive changes of the sensor repeat in the same frequency to the corresponding stimulus, suggesting that the sensor can respond to the pressure at frequencies of up to 5 Hz.

Figure 10 reveals the variation of the initial capacitance of the proposed sensor unit with bending radius of 3 mm, 5 mm, 9 mm, 13 mm, 17 mm and 22 mm, respectively. Red dotted line: polynomial fit of normalized output capacitance. Inset: bending at different radius.

Considering that human body temperature will effect on the performance of the textile tactile sensor, the experiment of temperature drift was investigated and studied by using the DZF-6021 vacuum drying oven. Figure 11 illustrates the capacitance variation under the different temperature settings. The initial capacitance changed under the temperatures varying from 25 °C to 35 °C, where the corresponding capacitance varied with temperature in an approximately linear relation, as seen in equation (4).

\[
\frac{C}{C_0} = 1.00119 + 2.5359 \times 10^{-4} \times P. \tag{3}
\]

Figure 8. Hysteresis error of the proposed device. Two consecutive measurements executed with increasing and decreasing force on the fabric sensor (the worst case has been reported).

Figure 9. Characterization of the time-resolved response of the sensor. The time-resolved sensor response measurements under repetitive mechanical loaded over frequencies from 0.1 Hz to 5 Hz (red curves indicate the input excitation to drive the electromagnetic pin actuator, and the black, red, and blue curves were the output capacitance measured from the textile tactile sensor).

Figure 10. The variation of the initial capacitance of the proposed sensor unit with bending radius of 3 mm, 5 mm, 9 mm, 13 mm, 17 mm and 22 mm, respectively. Red dotted line: polynomial fit of normalized output capacitance. Inset: bending at different radius.

Figure 11. The influence of temperature variation. The initial capacitance of the sensing device was measured under the temperatures varying from 25 °C to 35 °C.
$C_T/C_0 = 1.0176 - 3.497 \times 10^{-4} \times T. \quad (4)$

Where $C_T$ is the output capacitance at temperature $T$, $C_0$ is the initial capacitance (at 25 °C), $T$ is the current setting temperature. Temperature compensation can therefore be achieved based on the equation (3).

The distribution of relative error under different pressure and temperature conditions were analyzed in figure 12. Combining with equations (3) and (4), the temperature compensation algorithm was presented to compensate for the drift induced by temperature variations, which commonly affect capacitive textile pressure sensors.

4. Research on applications of textile tactile sensor

The proposed textile sensor is flexible, wearable and the measurement ranges are suitable for most of the biomechanical applications, especially for plantar pressure measurement [22] and manipulating soft-grasping [23], therefore, some application instances will included in the following paragraphs.

4.1. Classification of plantar pressure distribution

Plantar pressure is important in gait and posture research for diagnosing lower limb diseases, footwear design, sport biomechanics, injury prevention and other applications [24–26].

Figure 13 shows the design of a portable measurement system for plantar pressure distribution. Each insole consists of twelve textile pressure sensors, a CDC unit, and a wireless transmission module, etc. Fabric sensors were connected to the capacitive input pins of AD7147-1 through a flexible shielded cable and the active AC shield pin of AD7147-1 connected to the shielding layer of the tactile sensor to eliminate the parasitic capacitance. The CDC unit was designed on the FPCB and communicated with CC2530 through FPC.

To identify the distribution characteristics of plantar pressure during walking, we divided the steps into four stages, i.e. heel, entire foot, midfoot, and hallux. Figure 14 illustrates the test actions that correspond to the above stages. Figure 15 illustrates the test actions that correspond to the above stages. The corresponding results are depicted in figure 15.
4.2. Application of manipulator soft-grasping

The study of multi-finger robotic hands has attracted much attention in the past decades [27], and a manipulator with the capability of tactile perception plays a significant role on stable grasping and dexterous manipulation [28]. To further validate the applications of the proposed textile tactile sensor, we have also simply evaluated the minimum contact forces for rigid fingers. As described in figure 17, two textile pressure sensors were mounted on the manipulator thumb and forefinger, and used minimal force to pick fruit without any damage. The experiment results show that the proposed sensor provided a good guarantee for the robot to capture the object with stability and safety.

5. Conclusions

A capacitive wearable textile tactile sensor printed on a flexible textile substrate with a carbon black (CB)/silicone rubber (SR) composite dielectric was developed for bionic skin. The structure design, sensitive mechanism, and fabrication procedure of the sensor were illustrated. In addition, we characterized the characteristics of the device in terms of range, repeatability, hysteresis and time-resolved response. A temperature compensation model was introduced to improve the measurement accuracy and stability. Finally, the proposed tactile sensor has been successfully utilized to implement plantar pressure measurement and manipulator soft-grasping. The research results indicate that the reported device has potential applications in skin-like wearable electronics. Future work will focus on reducing the size of the device and printing a circuit board directly onto the fabric alongside the sensor to further integrate the system.

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