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Fabric Touch Sensors Using Projected Self-Capacitive Touch Technique

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We propose a touch sensor made of fabric that employs a projected self-capacitive touch technique as its sensing principle to achieve a large output signal. The touch sensor is made of fabric woven with conductive polymer-coated sensor fibers and it undergoes a change in capacitance when two sensor fibers cross under input applied pressure, which has been measured for detecting human touch. However, the change in the output capacitance of fabric touch sensors in previous studies has been small because the sensor fibers were narrow (i.e., <0.5 mm diameter) and the overlapping areas between fibers were very small. Therefore, we utilized a self-capacitive touch technique where the change in capacitance between sensor fibers and large width of human fingers (i.e., 2 cm wide) was measured to increase the overlapping areas of the capacitors on the sensor fibers. Thus, a larger change in capacitance of 2.44 pF was detected by the self-capacitance technique that we propose, while a small change in capacitance of 0.18 pF was achieved by using methods in previous studies. We demonstrated touch sensing with a 3×3 sensor fiber array and commercially available circuits to measure capacitance. We found that this technique was well suited to capacitive touch sensors made of fabric and it should lead to various applications.

1. Introduction

Touch sensors made of fabric have recently been developed by Professor Sato's team at Nagoya University for various applications including artificial robotic skin, wearable keyboards, and bed sensors.(1–3) Touch sensors made of fabric have advantages of being very flexible and inexpensive and having large areas. However, there is a problem of the small output signal with fabric touch sensors because the sensing mechanism is based on the capacitance between narrow fibers (i.e., <0.5 mm) and the sensing capacitance is extremely small (i.e., <1 pF).(1) If we use thick fibers, the fabric becomes too hard,

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resulting in devices that are too rigid. In addition, it is also difficult to amplify the signal with fabric touch sensors that have large areas because amplification circuits cannot be placed near them but are connected through long wires owing to the size of the sensors. However, the small capacitance of micro-electromechanical systems (MEMS) capacitive pressure sensors can be detected with capacitance measurement circuits inside the same sensor chip.(4) Therefore, for fabric capacitive touch sensors, it is important to study new ways of obtaining large output signals without placing amplification circuits near the sensors or using thick fibers. Previous studies on fabric touch sensors have reported on enlarging the sensor area,(1) measuring shear stress,(2) or improving the fabrication process.(5)

In this paper, we report fabric touch sensors that use the projected self-capacitive touch technique instead of the conventional mutual capacitive technique to achieve a large output signal. The capacitance between fibers and large human fingers (i.e., several centimeters wide) and larger capacitances were measured by the projected self-capacitive touch technique.(6) A comparative experiment on measuring capacitance by the projected self-capacitive touch technique and the previous mutual touch technique was carried out to evaluate fabric touch sensors. The touch sensors did not need to be measured with low-noise precision capacitance meters but with high-noise capacitance measurement circuits in small microcontroller unit (MCU) chips in practical applications. Changes in the capacitance of the sensors being touched were then measured with capacitance measurement circuits in small MCUs. Finally, points that were touched were demonstrated to have been detected with a touch sensor system that consisted of a 3×3 sensor array and capacitance measurement circuits.

2. Structure of Fabric Touch Sensor and Underlying Sensing Principle

The fabric touch sensor was woven from conductive polymer-coated fibers and pristine polyester fibers [Fig. 1(a)]. The sensing electrode was fiber, which was coated with a conductive polymer of poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) (H.C. Stark, Clevios PH1000) and a dielectric polymer of ultraviolet (UV)-curable adhesive (Tesk Corp. A-1864) as insulating and passivation layers, respectively. The PEDOT:PSS dry film was 1.35 μm thick, while the UV adhesive was 10 μm thick. The core of the sensing fiber was a Nylon fiber with a diameter of 485 μm. The fabric we examined had a 3×3 array of sensing electrodes at a pitch of 2 cm. Details of the fabrication process have been reported in a previous study.(5)

The sensing principle underlying the fabric touch sensor in this study involved measuring the capacitance between sensing electrode fibers and human fingers, as seen in Fig. 1(b)(2). This technique is called the projected self-capacitance touch technique and it is widely used in the touch screens of smart phones and tablet PCs.(6) Figure 1(b)(1), however, outlines the mutual capacitance measurement technique where capacitance occurs between fibers crossing each other. It has been widely used in previous studies on fabric touch sensors.(1–5)

Larger capacitances are measured by using the projected self-capacitive touch technique because the contact area of its capacitor is larger than that of the mutual capacitance measurement technique. Capacitance is defined by the contact area between a sensing electrode fiber and a counterelectrode. The contact areas [Fig. 1(b)(1)] between narrow fibers (diameters of 485 μm) are small in mutual capacitance measurements

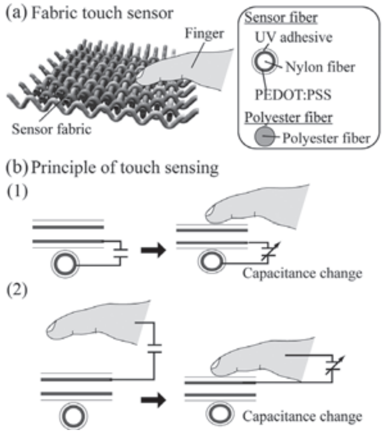


Fig. 1. (a) Configuration for fabric touch sensor. (b) (1) Sensing mechanism for mutual capacitance touch technique that detects change in capacitance between two fibers. (2) Sensing mechanism for projected self-capacitive touch technique that detects change in capacitance between one fiber and a human finger.

resulting in small capacitance. Consequently, sensors for mutual capacitance measurements are vulnerable to extrinsic noise. Therefore, the human finger (>2 cm wide) is replaced with fiber as the sensing electrode as the counterelectrode shown in Fig. 1(b)(2) to enlarge the contact area. This increases the capacitance between sensing electrode fibers and the human finger.

The capacitance between fibers and a human finger was estimated to be increased by ~26 times with a fiber diameter of 485 μm and a human finger width of 2 cm. This estimation was derived according to the following equations, where *C, S, d, ε, D,* and *W* are capacitance, contact area, gap between fibers and between the fibers and the human fingers, dielectric constant, diameter of fibers, and width of the human finger.

$$C_{\mathrm{mutual}} = \varepsilon \frac{S}{d} = \varepsilon \frac{\pi D/2^{*} \pi D/2}{d} = \varepsilon \frac{\pi^2 D^2}{4d}, \quad (1)$$

$$C_{\mathrm{self-capaciance}} = \varepsilon \frac{S}{d} = \varepsilon \frac{\pi D/2^{*} W}{d} = \varepsilon \frac{\pi D W}{2d}, \text{ and} \quad (2)$$

$$\frac{C_{\mathrm{self-capaciance}}}{C_{\mathrm{mutual}}} = \frac{2W}{\pi D}. \quad (3)$$

The capacitances are defined by the contact area S and gap d between a sensing fiber and a counterelectrode according to eqs. (1) and (2). The gap is constant because it is the thickness of the UV-curable polymer. Therefore, the capacitances depend on the contact area *S*. Thus, the increase in capacitance is derived with eq. (3). The change in capacitance with the projected capacitive technique is large because *D* is small and *W* is wide. For example, the increase in $C_{\mathrm{self\text{-}capacitance}}/C_{\mathrm{mutual}}$ is 26.3 when *W* and *D* are 2 cm and 485 μm, respectively. The increase by using projected self-capacitance touch sensing in experiments is compared with that using the previous mutual capacitance measurement in the next section.

3. Comparative Study on Measuring Capacitance in Touch Sensing

Figures 2(a) and 2(b) outline the measurement setups for the mutual capacitance and projected self-capacitance touch sensing techniques, respectively. The fabric touch sensors were connected to capacitance measurement equipment, which was a Hioki 3506 C HiTESTER, and the sensor was touched by a 2-cm-wide aluminum electrode, which worked as an alternative to a human finger.[8] The applied pressure was tuned by a force gauge with an integrated *z*-axis automatic positioning stage (Aikoh Engineering, Model FTN1-13A). The applied pressures could be varied from 1 to 20 N to detect the force that had to be applied to the sensors by using a positioning stage with a force gauge.

Figure 2(a) outlines the setup for the mutual capacitance measurements where the capacitance meter monitors the capacitance between two fibers that crossed each other. If pressure was applied to the crossing point, the contact area between fibers was increased, inducing a large capacitance between fibers. Figure 2(b), on the other hand, shows the projected self-capacitance measurements where the capacitance meter monitors the capacitance between one fiber and an aluminum electrode, instead of another fiber. The large contact area between the sensing fiber and wide aluminum electrode resulted in a large change in capacitance.

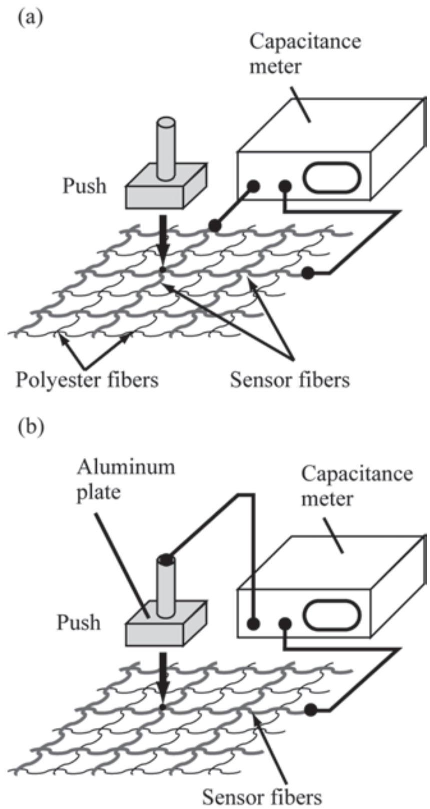
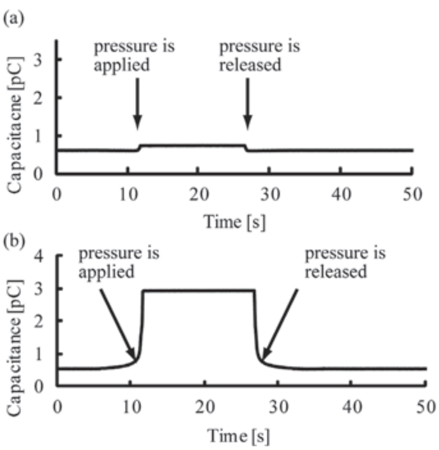


Fig. 2. (a) Experimental setup for mutual capacitance technique and (b) that for projected self-capacitance touch technique.

Figures 3(a) and 3(b) plot the changes in transient capacitance when a pressure of 1.25 N/cm^2 was applied to the sensor. A high measurement frequency of 1 MHz was used in the capacitance meter to reduce noise. Figure 3(a) indicates that the capacitance changed from 0.56 to 0.74 pF, resulting in an increase of 0.18 pF. However, the capacitance changed from 0.48 to 2.92 pF when using the projected self-capacitance touch technique, as shown in Fig. 3(b). The change in capacitance with the projected self-capacitance touch technique was 2.44 pF, which was larger than that using the mutual capacitance technique. In addition, because the change was larger than 1 pF, this range of capacitance could be measured with the conventional capacitance measurement circuits that are integrated into conventional MCUs.

Figures 4(a) and 4(b) plot the relationship between applied pressure and change in capacitance. The applied pressure ranged from 1 to 10 N/cm^2 because humans touch sensors at pressures of 1–10 N/cm^2. The change in capacitance increased in both cases, according to the increase in applied pressure. Compared with the increased rate of change in capacitance, the rate of mutual capacitance was large (200%). The change in capacitance increased from 0.09 to 0.27 pF when the applied pressure was increased from 1 to 10 N/cm^2 for mutual capacitance. The change in capacitance increased from 2.05 to 2.8 pF under pressures from 1 to 10 N/cm^2 for projected self-capacitance measurements. Therefore, the projected self-capacitance measurement technique is useful for measuring changes in capacitance with low noise because the absolute value of the change in capacitance is large (>2.05 pF). Note that the mutual capacitance technique offers a larger rate of increase for the change in capacitance than that for projected self-capacitance, which indicates that mutual capacitance is well suited to pressure measurements even though there are large amounts of noise.



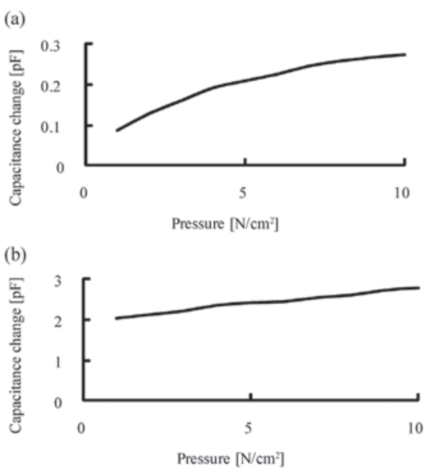


Fig. 3 (left). (a) Transient change in capacitance by mutual measurement technique and (b) transient change in capacitance by projected self-capacitance touch technique.
Fig. 4 (right). (a) Relationship between applied pressure and resulting change in capacitance by mutual capacitance technique and (b) relationship between applied pressure and resulting change in capacitance by projected self-capacitance touch technique.

4. Measurements with Fabric Touch Sensors Using Commercially Available Capacitance Measurement Circuits in ICs

We discussed low-noise precision capacitance measurement meters that were used to comparatively characterize capacitance measurement techniques in the previous section. In this section, we discuss commercially available capacitance measurement circuits whose large noise was utilized for practical use in our fabric touch sensors. The meters for precision capacitance measurements can generally detect hundreds of femtofarads (fF) of capacitance, whereas commercially available capacitance measurement circuits can detect several picofarads (pF) of capacitance.[6,7]

Capacitance measurement circuits in MCUs (Silicon Laboratories: C8051F700 DK) were used in the experimental setup. The capacitance measurement circuits have 38 pins, and their range of capacitance is up to 65 pF. We connected 3×3 sensors to the measurement circuits. The data we obtained were transferred to a personal computer (PC) through a USB cable. The capacitance data were collected from the software on the PC (Silicon Laboratories: C8051F700DK quick sensing development tools). The three column fibers in the sensor fiber array were labeled X1, X2, and X3, while the three row fibers were labeled Y1, Y2, and Y3.

Figures 5(a) and 5(b) plot the changes in capacitance on the X2 sensing fiber when a pressure of 1.25 N/cm^2 was applied with a 2-cm-wide aluminum electrode. Figures 5(a) and 5(b) indicate that noise is ~0.5 pF, and more than 0.5 pF for the sensor output signal is required to distinguish the sensor signal from noise. The change in capacitance was small by using the mutual capacitance measurement technique, and there was no increase in capacitance [Fig. 5(a)]. We detected a change in capacitance of 1.75 pF [Fig. 5(b)]by using the projected capacitive measurement technique. Therefore, no change in

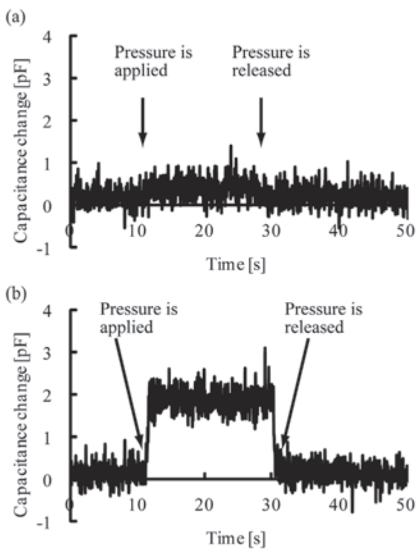


Fig. 5. Transient change in capacitance with commercially available capacitance measurement circuits. (a) Change in capacitance by mutual capacitance technique and (b) change in capacitance by projected self-capacitance touch technique.

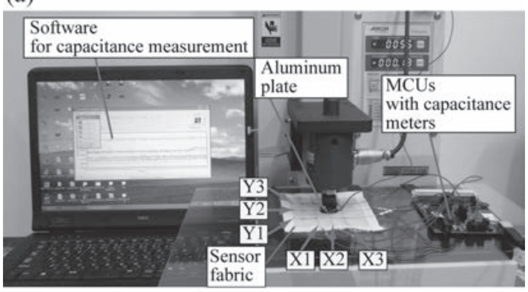
capacitance of less than 0.5 pF could be detected by using commercially available touch sensor capacitance measurement circuits owing to large amounts of noise if the mutual capacitance measurement technique was used.

Figure 6(a) is a photograph of the experimental setup. Figure 6(b) shows a table of the changes in capacitance in a 3×3 sensor fabric when pressure was applied. Pressure was applied to the crossing point of X2 and Y2 sensor fibers. The changes in capacitance in X2 and Y2 are larger than those in the other fibers. For example, the changes in capacitance in X2 and Y2 are 0.98 pF and 1.82 pF, respectively, while those in the other fibers are below 0.1 pF. Therefore, the point that was touched was the crossing point of the X2 and Y2 fibers. Therefore, the point that was touched was detected using the fabric touch sensors that utilized the projected self-capacitance touch technique.

5. Conclusions

The projected self-capacitance touch technique was employed as the sensing principle underlying fabric touch sensors to achieve large changes in capacitance. A large change in capacitance of 2.44 pF was detected by the proposed method of self-capacitance in a comparative study on mutual capacitance and projected self-capacitance touch techniques. In addition, the absolute value of increased capacitance by using the projected self-capacitance technique was found to be larger than that due to an increase in applied pressure. Touch detection was demonstrated even with commercially available capacitance circuits in MCUs by using this technique and a 3×3 sensing fiber array.

(a)



(b)

Sensor fibers	X1	X2	X3	Y1	Y2	Y3
Capacitance change [pF]	0.1	0.98	0.08	-0.1	1.82	0.09

The point crossing X2 and Y2 fibers is touched

Fig. 6. (a) Experimental setup for 3×3 fabric touch sensors using commercially available capacitance measurement circuits. (b) Table of changes in capacitance for 3×3 fabric touch sensors.

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