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Development of a polymeric capacitive 3-D tactile sensor

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Abstract

In this paper, we present a novel polymeric 3-D tactile sensor. The tactile sensor comprises of a flexible quad capacitor array where three axial forces can be measured from the sensors' relative areas and gap distances changes using a simple differential equation. To improve the overall performance of the sensor, several high dielectric polymers were developed so that a smaller sensor area ($< 1 \times 1 \text{ cm}^2$) can be achieved. A specially designed LC circuit was also developed to improve the capacitance detection. With the current configuration, the sensor is capable of detecting forces in any arbitrary direction with a sensitivity of 0.1N and a force range up to 45N.

Keywords

tactile sensor; flexible sensor; 3-D tactile sensor; capacitive sensor

INTRODUCTION

Force sensor is an important component in technologic research and industry. The development of force sensor has gone forward greatly in these days. According to market analysis, the global market of the sensor will grow to 61 billion in 2010 because of industrial automation [1]. However, traditional force sensor cannot detect shear force precisely and the sensor cannot be bent which would limit the area of the application of the sensor. 3-D flexible tactile sensor proposed in this paper can extend the application of force sensor such as being applied to medical and athletic research.

There are many kinds of tactile sensors based on different detecting principles. Techniques include piezo-resistive [2, 3], capacitive [4], piezo-electric [5], optical [6], inductive [7], and acoustic [8] tactile sensors [9]. Among these different types of sensors, piezo-resistive, capacitive and piezo-electric sensors are most commonly used for flexible tactile sensor due to its size and simple design.

Piezo-resistive sensor uses conducting materials with high pressure sensitivity to detect the force. The resistance of silicon changes not only due to the stress dependent change of geometry, but also due to the stress dependent resistivity of the material. The most widely used semiconductor gages are piezoresistive based silicon devices. These sensors have a very linear mechanical and electrical response almost free of any noticeable hysteresis effect [9]. They also have a relatively low thermal expansion coefficient ($\text{Si} = 3.5 \times 10^{-6}/^{\circ}\text{C}$) compared to metals [11]. The disadvantages include its breaking stress (ranging from 0.41–2.1 GPa, depending on the diameter of the deformable element) [12]. The devices are relatively stiff (Young's modulus around 130 GPa), and can handle a maximum strain around 0.5% [12]. These devices are therefore mainly for micro strain measurements, and are not intended for large deflections. In addition, the materials are stiff and brittle and require additional packaging to allow the sensor to be able to interact with soft surface.

Piezoelectric materials are also commonly used for strain/stress measurement. A piezoelectric material generates an electrical charge when subjected to mechanical stress. The most widely used piezoelectric materials are electric polymers, such as polyvinylidene difluoride (PVDF or PVF_2) [13, 14]. The advantage of using PVF_2 film is that it is flexible and can withstand rather large strains without severe deterioration. Films can be manufactured in thickness ranging from a few microns to a few millimeters. However, the material is structurally weak and prone to damage. In addition, the material suffers from poor fatigue life and from shrinkage due to aging and temperature [15]. The sensitivity of piezo-electric sensor sensitivity is also lowest among all the sensors.

Capacitive based transducers such as EMED and PEDAR (Novel GmbH, Munich, Germany) are widely used for distributive pressure sensing. Although both provide high accuracy and wide range of force measurement, capacitive sensors in general are susceptible to electrical interference and may suffer from low spatial resolution, drift, and a high sensitivity to temperature. But, more importantly, as with F-SCAN, both types of Novel sensors are only able to measure plantar pressure, not shear.

In this paper, we will present a new approach to the capacitive sensor to address problems previously plaguing the EMD, PEDAR sensors by using a polymer based quad sensor array and a new electronic detection system. In addition, a novel capacitor array design allows both pressure and shear to be detected.

THEORY

The working principle of sensor is converting physical and chemical properties such as pressure, temperature, velocity to electric properties. Thereafter, the electric signal can be acquired and recorded to analyze the varying physical and chemical quantities. Capacitive sensors consist of a pair of conductors separated by a dielectric material. An electric field between the conductors is present when there is voltage across the conductors.

The ratio of the electric charge on each conductor to the voltage between them is defined as capacitance.

$$q(t) = C'v(t) \quad (1)$$

q : Electric charge [Coulomb]

C : Capacitance [Farad]

v : Voltage [Voltage]

The value of capacitance is related to the area of the conductor and the distance between them, which can be written as,

$$C = \frac{\epsilon_0 \epsilon_r A}{d}; A \cdot d^2 \quad (2)$$

$\epsilon_0 = 8.854 \times 10^{-22}$: Vacuum dielectric constant

ϵ_r : Relative dielectric constant of dielectric material

A : The area of electrode [m^2]

D : The distance between electrodes [m]

Applying force on the conductor would cause the distance “ d ” to change and the capacitance between the conductors to change, therefore the force could be known by measuring the varying capacitance. However, it can only show one axis of force from one pair of conductors. In this paper, a quad capacitors array design, shown in Figure 2, enable three axes of force to be measured. The sensor is consists of four capacitors sharing a common ground electrode. A dielectric material is sandwiched between the four divided electrodes on the bottom and a common electrode on top. The basic concept of the sensor is as follow:

When there is no applying force on the sensor, the capacitance of the sensor is equal to

$$C_a = C_b = C_c = C_d = \frac{\epsilon_0 \epsilon_r a^2}{d} \quad (3)$$

Where C_{a-d} are capacitance values for between upper electrode a-d and top common electrode.

When a force is applied parallel to the X axis (Figure 3), the cover area of C_a and C_d will decrease by the amount of the remaining overlapping area,

$$\begin{aligned} C'_a &= \frac{\epsilon_0 \epsilon_r a(a-x)}{d} \\ C'_d &= \frac{\epsilon_0 \epsilon_r a(a-x)}{d} \end{aligned} \quad (4)$$

On the other hand, C_b and C_c can maintain the same capacitances because of the unchanging area and distance. Figure 4 shows the same effect would be observed when a parallel force is

applied along Y axis. For a force is applied along Z axis, the distance between the top and bottom electrodes decreases (Figure 5) thus capacitances increase.

For a force applied in an arbitrary direction where force is consisted of the three above directions (Figure 6), the four capacitances are related to the change in area and distance, and could be written as,

$$\begin{aligned} C'_a &= \frac{\varepsilon_0 \varepsilon_r a(a-y)}{d-z}; \\ C'_b &= \frac{\varepsilon_0 \varepsilon_r (a-x)(a-y)}{d-z}; \\ C'_c &= \frac{\varepsilon_0 \varepsilon_r a(a-x)}{d-z}; \\ C'_d &= \frac{\varepsilon_0 \varepsilon_r a^2}{d-z}; \end{aligned} \quad (5)$$

By rewriting the above equations, we can derive the ratio of three displacements as

$$\begin{aligned} xx &\propto \frac{(C'_a + C'_d) - (C'_b + C'_c)}{C'_a + C'_b + C'_c + C'_d}; \\ yy &\propto \frac{(C'_a + C'_b) - (C'_c + C'_d)}{C'_a + C'_b + C'_c + C'_d}; \\ zz &\propto \frac{C'_a + C'_b + C'_c + C'_d}{C'_a + C'_b + C'_c + C'_d}; \end{aligned} \quad (6)$$

EXPERIMENTS AND RESULTS

The capacitance is related to the area and the distance between each electrode, making the accuracy and the precision of the electrodes are very important. To increase the accuracy, we use laser CO₂ instrument to cut the acrylic base-plate and electrodes. The overall geometry of the sensor is about 0.4×1×1cm³. Since the sensor is highly sensitive to the thickness, spin coater and molding were use to fabricate the dielectric layer of the sensor. The structure is packaged in an elastomeric polymer that is specifically selected to withstand the desired loads and also provide a good restoring property. The acrylic plate helps align the upper and lower electrodes.

Sensor was first calibrated by applying a small force under 4.5N with a small incremental force of 0.5N and then a larger force to 45N at a larger 5N interval (Figure 6). Based on the results, we found that the sensor has a sensitivity of 0.1N and range of 45N (but probably close to 65N based on extrapolation from the Figure 6b). The range is only limited by the range of the LC circuit (maximum range of 3pF) and also by the material we used for the sensor substrate. This current sensitivity and range is as good as any commercially available tactile sensor array.

Another test was done by applying an inclined force at 45 ° angle along xz plane. As shown by the results in Figure 7, the displacement caused by the moving upper electrode reduced the cover areas of the two capacitors where the upper electrode is moving away from. This resulted in a reduction of the capacitances of these two capacitors (C_a and C_d). However compare with the other two capacitors, the reduction does not seem to increase as rapidly as the capacitances increase in the other two capacitors. This is due to the fact that these two capacitors with increasing load, their gap space or thickness of the dielectric layer actually

also decrease so that overall capacitance changes are compromised. On the other hand, the two capacitors (C_b and C_c) are increase due to increasing load. This is expected since the cover area of these two capacitors is not increasing. However the gap spaces of these two are continue to decrease. Therefore the capacitances are showing more drastic increase compare to the reduction in the other two capacitors.

To improve the capacitance detection, a specially designed LC circuit was developed. The current sensor has a capacitance value in the range of few pico farads. This is very difficult to measure with any existing commercial RC or LC meters. This is compounded by the fact that there are other capacitance effect coming from wires and other background RF interference. The uniqueness of this LC circuit is that it has a resolution of 0.1pF and a range of 3pF. Aside from being able to measure small capacitance, the circuit also converts capacitance to voltage which allows an easier integration with the external data acquisition system. In addition, a special shielding and tightly packed circuit provides a highly stable signal. The capacitance versus converted output voltage is shown in Figure 7. The circuit has a conversion factor of 1.17V/pF.

To verify the performance of this LC circuit, the changing voltage was compared to the applying force. The vertical applying force increased the output voltages of the four capacitors uniformly (Figure 9). In the case of 45 ° elevated applying force, there are two voltages increase but two with small decrease (Figure 10), which is same as the result in capacitance test shown in Figure 7.

Using equation (6), the three axial displacements can be derived from the capacitances measurement of these four capacitors; or in this case from the voltage obtained by the LC circuit. Using the results obtained from Figure 10, we generated the displacement in the x, y and z direction shown in Figure 11. As expected, most displacement occurs in the x direction since the applied load was directed along that direction with an elevation angle of 45°. Even though the force in x and z directions are equal, the displacement in these directions based on the calculation are not equal. The difference of displacement between these two directions simply by applying equation (6) simply ignore the fact that the material has a preferential movement in the horizontal direction due to the fact that the sandwiched layer is made of an thin elastomeric material. Because of the geometry of the layer and also the larger shear compliance of the material, the displacement in the x direction is showing larger displacement than in the z direction. The displacement in y direction varies slightly is mainly due to the instability of this prototypical sensor. It is most likely due to the fact the material got squeeze and create unwanted movement in the y direction.

CONCLUSION

Through the above experiments and results, it can be concluded that by combining the novel array design and LC circuit design proposed in this paper, the capacitive 3-D tactile sensor can measure 3-D force and displacement effectively. Additionally, the sensor has a miniaturized dimension ($0.4 \times 1 \times 1 \text{ cm}^3$) which can detect in the range between 0.1N to 45N. The miniaturization, wide detection range, and the flexibility this novel 3-D tactile sensor could be utilized to the medical and athletic field expectably.

Acknowledgments

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Figure 1.
Electric field between two plates.

Figure 2a. Top view of 2x2 array capacitors sensor.

Figure 2b. Side view of array capacitors sensor.

Figure 2.

Figure 3a. Top view of force applied along X axis.

Figure3b. Side view of force applied along X axis.

Figure 3.

Figure 4.
Top view of force applied along Y axis.

Figure 5.
Side view of force applied along Z axis.

Figure 6.
Top view of force applied in random direction.

Figure 6a. Vertical force from 0N to 4.5N.

Figure 6b. Vertical force from 0N to 45N.

Figure 6.

Figure 7.
Plot of capacitance versus applied force. (Force applied at an inclined angle 45°).

Figure 8.
Plot of capacitance and converted voltage versus applied force.

Figure 9.
Voltage change of vertical applying force.

Figure 10.
Voltage change of 45 ° applying force.

Figure 11.
Three axes of displacement calculation of 45 ° applying force.