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A Flexible Tactile Sensor Array Based on Conductive Rubber

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***Abstract*— In this paper, a novel flexible tactile sensor array based on conductive rubber is presented. Compared with other research results, we use the materials with complete flexibility to fabricate the soft sensors. The sensing prototype includes polydimethylsiloxane (PDMS) as the sealing layers and conductive rubber as sensing layer. This proposed tactile sensor can measure the contact pressure under wrapping one curved surface. In our study, we developed a skin-like tactile sensor array from three aspects: design procedures, fabrication techniques and test results via taking one 8 ×8 sensor array for example, which is a sandwich structure and the sensing material was laminated into a thin encapsulation film with 2mm in thickness. Furthermore, the sensor overcomes the fabrication complexity, chemical unsafety and environmental instability problems to some extent. In the end, the final experimental demonstration verify the feasibility of the sensor array with discrete sensing elements in measuring the tactile force via matlab.**

Keywords— Tactile sensor array, conductive rubber, PDMS, curved surfaces, wearable device

I. INTRODUCTION

Tactile sensors play a vital role in wearable, human-centered devices and have been the focus of recent soft robots. In our perspective, sense of touch, curvature, and length are critical in terms of effective and safe interaction for the communication between robots and other outside humans/things. Currently, in the fields of robots especially the soft robots, the flexible tactile sensors have very popular applications[1-5].

In the last several decades, researchers from various countries have engaged in developing novel sensing technology or sensors to satisfy the need of soft robotics. Until now, there are different sensing principles such as piezoresistive effect [6-12], capacitance change[13-15], optical wave-guides [16-18], miniature inertial theory [19-23], magnetic effect [24,25] and so on are all proved to be feasible to achieve the tactile sensing capabilities. Recently, the new attempt of soft artificial skin-like sensors using embedded micro-channels fulled with conductive liquid metal appeared [26-39]. However, the flow behaviour of liquid material still exists fabrication and sensing performance constraints in terms of practical application .

In our study, we attempt to design a tactile sensor array using discrete conductive rubber elements in order to form flexible interconnects. The design model, fabrication process as well as the performance of the sensor array have been presented. The results presented in this paper may be instructive for further research.

II. STRUCTURE DESIGN

The schematic of the sensing array is described in Fig. 1, Referencing to the Fig.1 we can see that the sensor is totally fabricated with soft materials including PDMS and conductive rubber. The fabrication strategy is mainly shape deposition manufacturing (SDM). The molds used to make silicone rubber film were fabricated via 3D printing. And two silicone rubber films are used as encapsulation layers. The conductive rubber (3M Company, Maplewood, Minnesota, U.S) is employed as the sensitive material. The resistance of the 3M conductive tape will change with increase of external load in vertical direction. Table I shows that electrical and physical properties of the conductive tape.

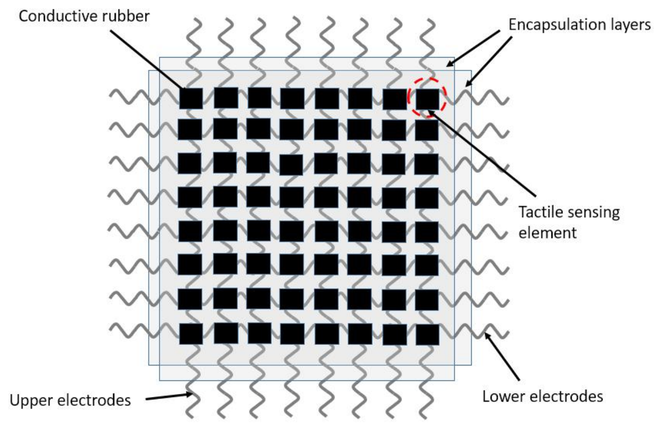


Fig. 1. The structural diagram of the proposed tactile sensor array

The sensor structure is consisted of the encapsulation layer, sensing layer and conductive thread. The two layers of conductive threads are parallel and placed in 8 rows, and the length of threads are a little bit longer thatn the width or length of the encapsulation layer. Repeat that step in order to make the second encapsulation layer with conductive threads. Place them ready to be used. Then the conductive rubber is tailored into some square elements in proper size in order to be placed in the positions of the intersection of the two electrode layers(the finished part: encapsulation layer and conductive threads) . Noticed that two electrodes layers are fitted perpendicular to each other. Each intersection is a sensing unit. When a external force is applied on the sensing unit, the resistance between conductive threads and sensing film would decrease, which easily obtained the relationship between the external pressure and the resistance. The tailored square sensing units can contribute to flexibility to some extent. For example, the tactile sensor array can wrap around the back of on human hand with no gap while maintaining good conductivity, as shown in Fig. 2.

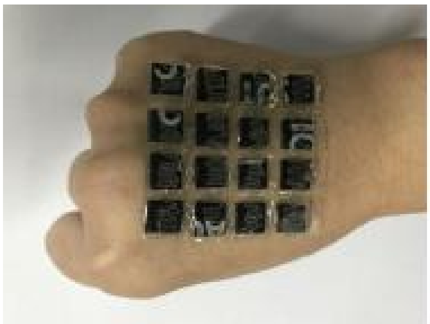


Fig. 2. A 4*4 sensor array covering the back of the hand

Table I Typical Physic and Electric Properties of the Conductive Rubber

Tensile strength	6lbs/in
Elongation at break	800%
100% modulus	860KPa
Volumm resistivity	103Ω-cm
Temperature rating	194°

III. MEASUREMENT PRIINCIPLE OF THE SENSOR

Conductive rubber belongs to piezoresistive materials, which mostly mixed by a certain amount of electric conductive fillers which is homogeneous and distributed uniformly in one of non-conductive elastomer (for example, rubber). Fig. 3 shows the formation mechanism of the conductivity of the conductive fillers included by the conductive rubber, which researched by Wang. etc.[40].

We can find the conductive fillers do not touch each other, that is to say, there is no or few electricity passing through the fillers (the white oval parts of the figure) when there is no external force applied on the conductive rubber, So the material presents high electrical resistance. While, when the external force acts on the conductive rubber, the volume is compressed and some conductive fillers could form the network chain or contact closer. The electrical resistivity decreases, then these lead to the changes in the resistivity.

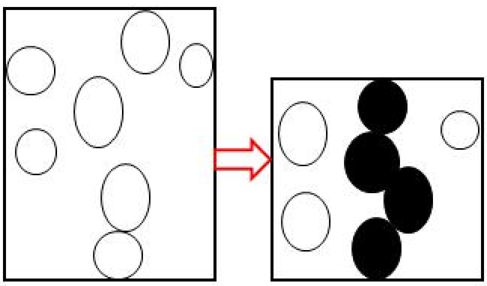


Fig. 3. Schematic diagram of typical conductive path

IV. STRUCTURE DESIGN AND FABRICATION

A. Structure Design

The measurement principle of the tactile sensor array is shown in Fig. 4.

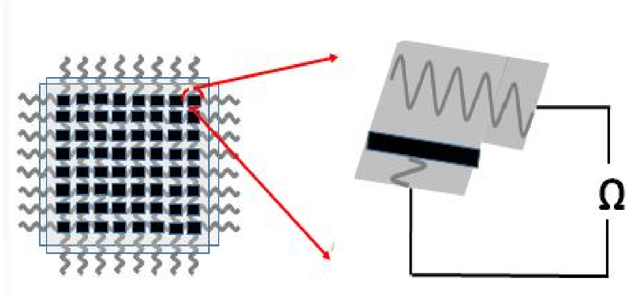


Fig. 4. The measurement principle of the tactile sensor array.

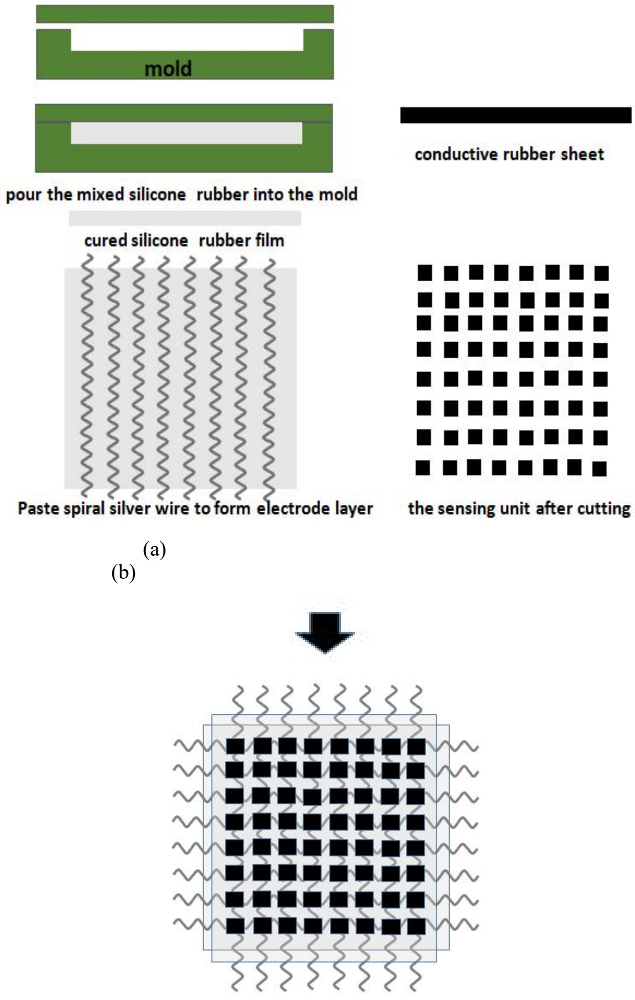
In the sensor array , the silicone rubber films pasted on the electrodes caller, are used encapsualtion layers and the sensing layer is made by conductive rubber as piezoresistive material.

Two layers of conductive threads are placed in perpendicular direction that the metal wire electrodes in one encapsulation layer is orthogonal to the wire electrodes in another layer. It worth mentioning that the encapsulation layers are made from silicone rubber (Rockwell hardness of 0), which contributes to the flexibility mostly. In addition, the encapsulation layers also protect the internal materials include the conductive threads and conductive rubber. Hence, we can conclude that the designed tactile sensor array has pressure sensing capability and device flexibility.

B. Fabrication Procedure

In order to maintain the flexible ability of the senor, the whole plate of conductive rubber is tailored into some small square pieces, and each piece is employed as a sensing unit. In addition, all the molds in the fabrication process were made via 3D printing.

Because the tactile sensor array includes the upper and lower encapsulation layers with conductive threads and the tailored sensing elements. The metal threads are pasted on the two encapsulation layers perpendicularly to form a matrix sensing mechanism. Because the metal wires are not stretchable, we pasted the wavy metal wires on the encapsulation layer to prevent conductive wire from breaking when the sensor array has some deformation. Fig. 5(a) shows the fabrication process of top and bottom electrodes layers. Firsly, the casing molds was machined by 3D printer (Makerbot Replicator, U.S) with the desired shapes. It is worth mentioning that all the molds involed in this paper were made via 3D printer. Then we cleaned it with 70% Ethanol and put the mixed liquid silicone rubber (Rockwell hardness of 0, semitransparent, the ration of base to cross-linker is 1:1 by mass) into an oven at 60℃ for 0.5 hour. The temperature of 60 ℃ helped to dry the liquid silicone rubber. The mixed solution was degassed and poured into the groove of the mold to form a thin film as the encapsulation layer with about 0.5mm thickness. Next, we peeled off the silicone rubber film of 0.5mm from the mold carefully. Then 8 metal threads were pasted on the liquid silicone films in waves to form the conductive eletrodes of the sensor. With the metal wires affixed to the silicone rubber with Semi-cured silicone rubber, the 8×8 tactile sensor array could be formed successfully.



(a)
(b)

(c)

Fig. 5. Flexible pressure sensor array fabrication process: (a) electrode layer; (b) sensing unit; (c) sensing array

The sensing units is made as shown in Fig. 5(b). The tailored sensing sheet has 30mm in length, 30mm in width, and 0.76mm in depth. We tailored the rectangle sheet into small square pieces (2mm×2mm).

When the top and bottom silicone rubber films as well as piezoresistive elements were aligned together in order to satisfy the conductive threads are orthogonal to each other and the sensing elements are sandwiched between two threads, as shown in Fig. 5(c). Then the three layers were laminated together by brushing liquid silicone rubber along the sides of the layers. Curing the mixed, degassed liquid silicone rubber, the sensor array were fabricated finally, as shown in Fig.6.

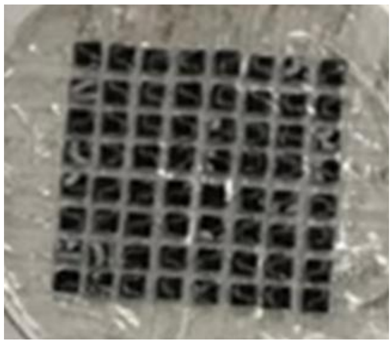


Fig. 6. The photoshop of an 8*8 sensor array

V.EXPERIMENTS AND DISCUSSION

A. Scanning circuit design

This paper adopts the piezoresistive sensor array which composes of parallel electrodes, sensing unit external wires, called upper (rows) and lower (column) electrodes, are perpendicular. Piezoresistive rubber pieces are fixed in the middle of the cross of top and bottom electrode layers. Pressure sensor array using the Row-Column electrode structure, and the main purpose is to reduce the number of signal processing circuit external threads.

However, the sensor array signals of Row-Column electrode structure between adjacent sensing units are easy to produce cross – talk effect. Therefore, this study adopted a Zero potential method to reduce the impact, as shown in Fig. 7.Voltage is applied to each row in turn, and the rest of the line voltage is set to zero. The ends of all the columns are connected to the signal readout circuit and all voltage values are set to zero. This approach can eliminate measurement error due to leakage resistance efficiently. The equivalent circuit of each sensor unit is shown in Fig. 8

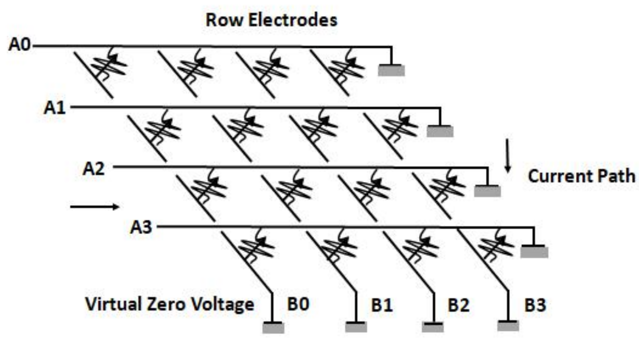


Fig. 7. Zero potential scanning

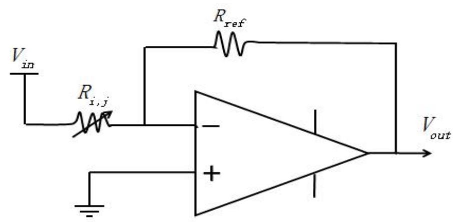


Fig. 8.The equivalent circuit diagram of each sensing unit after adopting zero potential method

The calculated voltage could be deduced :

$$V_{out} = -\frac{R_{ref} \bullet V_{in}}{R_{i,j}}$$

(1)

Where V_{in} is the constant voltage input of the circuit, R_{ref} is the constant divider resistance and $R_{i,j}$ is defined as the resistance for each sensing element .

B. Test experimental Setup

In this chapter, we conduct some experimental tests. An 8 × 8 sensor array, signal processing circuit and GUI graphical user interface built via Matlab. The hardware involved in this system is shown in the Fig. 9.

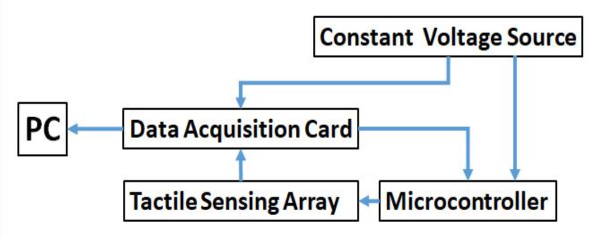


Fig. 9. Tactile sensing system

I/O ports P0-P15 of Microcontroller (stm32f103vet6) are linked with every line of sensor array to control the scanning parameters. Assistant I/O ports are connected to the data acquisition card (PCI-1710, Taiwan) in order to receive control commands. Port VIN (unregulated power in) and port VSS (system ground) is connected to a constant voltage source.

The graphical user interface (GUI) of the 8 × 8 tactile sensor array is provided to illustrate the external force magnitudes and display interface was programmed via Matlab. It has three main functions: the open and close buttons of the scanner; reading outputs from data acquisition card; illustrating pressure distribution. When scanning circuit is working, every line of power supply time is set to 32 ms-50ms. The user interface color depth corresponding to the magnitude of the applied pressure. The greater the applied pressure is, the deeper the color shows.

C. Measurement results

Referencing to Fig. 10, the experimental setup for obtaining the force value and displayed via one computer.

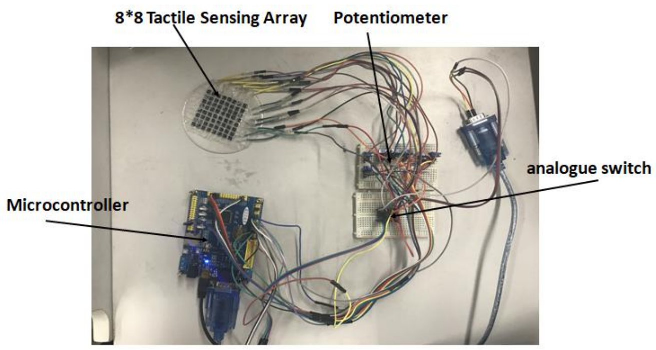
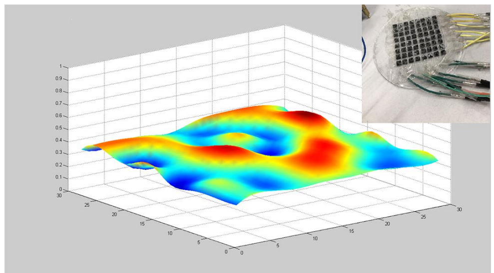


Fig.10. The experimental setup for measuring the resistance of the sensing element.

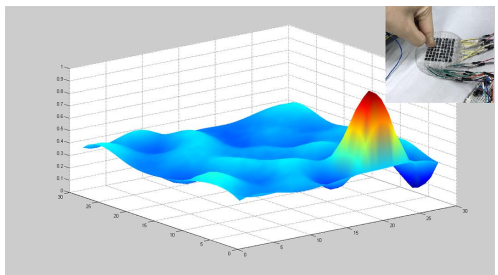
A 8 × 8 tactile sensing array has been put on force-balance test . We observed minimum resolution could as low as 0.01g. Because of the shown mass applied by the finger or other objects, we can deduce the external force applied on one sensing unit. Make sure that the external force should be placed under a z-axis (vertical) direction.

For the subsequent performance tests, the designed tactile sensor array is calibrated by standard instrument with high precision. Thus the relationship between the output and input of the sensor is established. The performance is excellent when the applied pressure started from 30kPa increasing 500kPa and decreasing to 30kPa in one test. The resolution is 1 element per 4mm^2 area. Besides the sensing array also exhibits stable resistance which is one of the desired behaviors of the flexible tactile sensors after all kinds of twists.

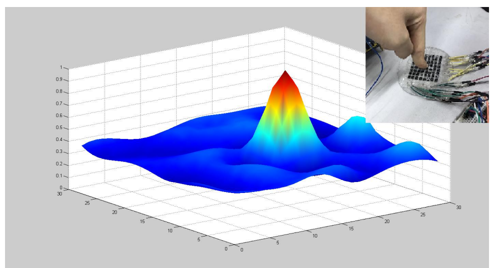
Fig. 11 shows that the upper computer display (matlab) can accurately identify the pressure position and magnitudes of the 64 points. Fig. 11(a) shows that when there is no pressure, PC displays no humps and Fig. 11(b) and Fig. 2(c) shows that when pressure is applied to two different points, the upper computer can clearly identify the position and magnitudes of the pressure point.



(a)



(b)



(c)

Fig. 11. PC displays pressure distribution when no pressure and two different locations are applied.

VI. CONCLUSION

Soft sensors have great potential for applications, especially for the monitoring, the optimization and the control designs of wearable devices. In this paper, we developed a flexible tactile sensor array based on PDMS and conductive rubber, which is very easily understandable from the design principle, fabrication techniques. Moreover, the corresponding experimental results for 8×8 tactile sensing array are presented, which is very convincing for the success design and fabrication. As a whole, the sensor overcomes the fabrication complexity, chemical unsafety and environmental instability problems to some extent.

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