



Research and design of a novel, low-cost and flexible tactile sensor array



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ABSTRACT

At present, the flexible tactile sensor array has become a hot research topic in the field of robotics. This paper introduces the design, fabrication and measurement of a novel tactile sensor array based on soft materials and sensor's piezoresistivity. This sensor array is capable of detecting the contact force and contact location via a triangular location algorithm. This triangular algorithm, which uses response of different sensing elements to a contact force, can reduce the amount of processing data and the density of the sensor array can get lower. The flexible pressure sensing elements are integrated in a flexible PDMS (polydimethylsiloxane) film, which can avoid the limitation that traditional rigid sensing elements have during their bending deformation. The sensor array's performance has been experimentally evaluated. The results show that the proposed sensor array has an accuracy of 88.23% for the force and spatial resolution of the sensor array can reach 2.5 mm.

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1. Introduction

With the continuous development of robot research, the robot tactile has become a hot research topic. The tactile sensing information is the basis for manipulation [1], as the information can provide the target object's mechanical properties such as shape, friction and stiffness for the controller. Modern autonomous robots, which are expected to coexist with humans, adapt different surroundings and finish complex tasks, need tactile sensing [2] to meet these requirements. Therefore it is important to design a flexible and low-cost tactile sensor for robot research.

In order to cope with this increasingly imperious demand, many tactile sensors have been invented over the past thirty years [3]. These sensors use different sensing elements and sensing principles such as piezoelectric [4], piezoresistive [5], capacitive [6,7], optical [8], magnetic [9], and carbon nanotubes [10]. Now a research trend of the tactile sensor is to be flexible, which can let the sensor joint robot surface and feel the bending deformation of the touched object directly. The Young's modulus is a physical quantity which is usually used to estimate the flexibility of material. For humans, the different parts of the skin have different Young's modulus. The Young's modulus of human skin is from 0.02 MPa to 100 MPa [11]. Therefore, the Young's modulus of the skin material should be less than 100 MPa in order to meet the flexibility. Murakami et al. [12] designed a kind of robot flexible finger based on a six-axis force/torque sensor and silica gel. They

embedded the sensor into the silica gel and used silica gel as a flexible medium of force transfer. Takao et al. [13] also embedded transistor arrays into polymer doped with graphite to detect contact force and temperature. These sensors' substrates are soft. However they are still limited in bending deformation, because the sensing element is rigid and the soft materials are only used as medium of force transfer. By using special structure of polymer substrates, Engel et al. [14] fabricated a flexible tactile sensor array that can identify objects based on texture, temperature, as well as material properties such as hardness and thermal conductivity. These sensing elements are nickel resistances. These tactile sensors' sensing elements are still rigid, but they all use special structure to moderate the limitation of bending deformation. Ho and Hirai [15] utilized a Nitta I-SCAN50 tactile sensing system that consists of a grid of tension-sensitive electroconductive ink lines to get tactile data. They used image processing algorithm to process the tactile data in order to get high resolution. The sensing elements of this tactile sensing system are soft so that the sensor can detect the grasped object's position/orientation, contact shape and the stick-slip condition on the contact surface without the limitation of bending deformation. However, to realize these functions, AV Ho's method has highly time-consuming to process the tactile data, especially in a high density and large area sensor array.

In this paper, in order to realize flexible sensing element and reduce processing data, we design a novel and flexible tactile sensor array based on PDMS (polydimethylsiloxane) whose Young's modulus is about 5 MPa. The sensing element is an Interlink Electronics FSR400 (force sensing resistor) which is based on soft polymer thick film. FSR has lower temperature drift. Force accuracy of

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FSR sensor ranges from approximately $\pm 5\%$ to $\pm 25\%$ depending on the consistency of the measurement and actuation system. The force resolution of FSR devices is better than $\pm 0.5\%$ of full use force. This soft sensor can get pressure data without the limitation of bending deformation. Compared with other high density array [15–17] consisted of commercial force sensors and other tactile sensors based on PDMS [18,8,19], we process pressure data by a location algorithm which can accurately calculate the position of the touch point and the computational cost is smaller than conventional processing algorithm.

The rest of this paper is organized as follows. In Section 2 we outline the structure of the sensor array and in Section 3 we analyze the structure of the sensor in mechanics and introduce the location algorithm. In Section 4 we do a finite element analysis of the sensor array and in Section 5 we report real world experiments. Finally, in Section 6 we draw our conclusions and sketch the future work.

2. Design and fabrication of sensor array

To solve the problem of flexibility, we use flexible substrates and flexible sensing elements to form a flexible sensor array. The flexible substrates are constituted by PDMS and the flexible sensing elements are constituted by FSRs which are based on piezoresistivity. These FSRs are placed in accordance with the equilateral triangle whose sides are 20 mm, which formed four equilateral triangle areas. Fig. 1 shows the diagrammatic sketch of the sensor array.

The sensor array was fabricated by a rectangular mold. The PDMS liquid and the hardener are mixed evenly by weight ratio 10:1. Then spoon a part of the mixture carefully into the mold until the thickness of the mixture in the mold reach 2 mm. Use a tweezers to move FSRs on the surface of the mixture. These FSRs are placed in accordance with the equilateral triangle. Spoon the remaining mixture into the mold and put the mold in a vacuum drying oven for 30 min. Finally, place the mold in the room temperature for forty-eight hours.

Fig. 2 shows the photo of the sensor array. The sensor array's prototype is an elastic PDMS film. This PDMS film is 80 mm in length, 80 mm in width and 8 mm in height. The weight of this film is 50 g, and there are six FSRs implanted in the film and located on the same horizontal plane which is 6 mm from the surface. FSR's thickness is 0.3 mm and the diameter is 5 mm. The multiple copper cores are adopted as the connecting wires, which have the advantages of higher flexibility, excellent heat radiation and durability.

3. Mechanical characterization of sensor array and location algorithm

3.1. Mechanical characterization

In order to facilitate the analysis, it is assumed that the elastic body material is homogeneous and isotropic and the contact area is infinite in one direction in three-dimensional space [20].

We create a coordinate system as shown in Fig. 3 (y-axis represents the depth, and x-axis and z-axis represent the upper surface). According to the elasticity theory principle, the stress of any point (y, z) in cross section of the elastic layer can be expressed as

$$\sigma_y = \frac{2y^2}{\pi(y^2 + z^2)^2} (yF_y + zF_z) \quad (1)$$

$$\sigma_z = \frac{2z^2}{\pi(y^2 + z^2)^2} (yF_y + zF_z) \quad (2)$$

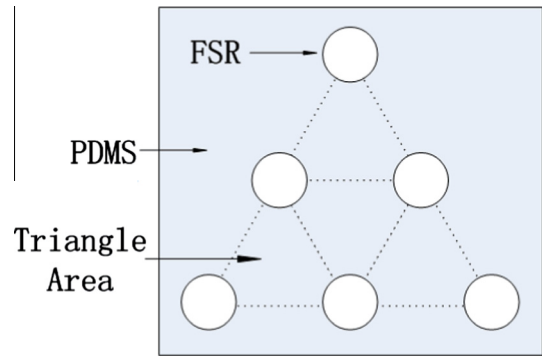


Fig. 1. Schematic of the sensor array.

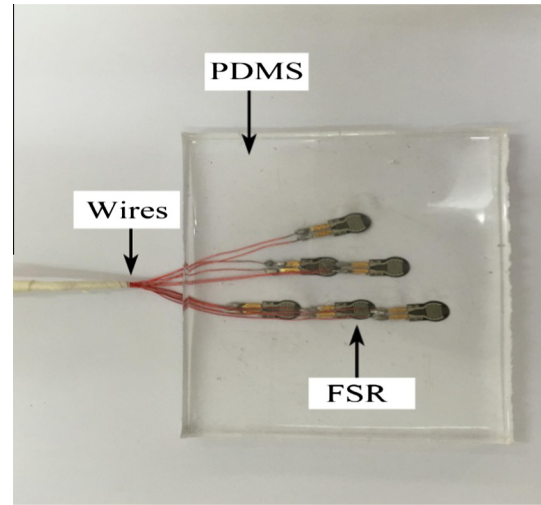


Fig. 2. Photo of the sensor array.

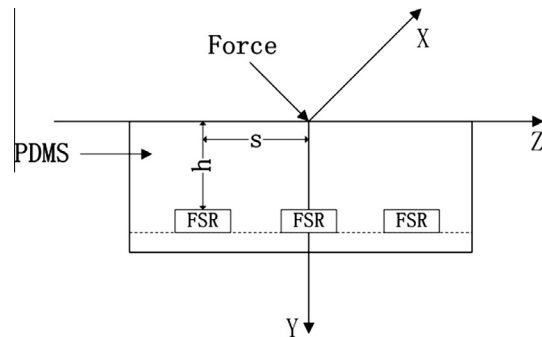


Fig. 3. Sectional view of sensor array.

where σ_y and σ_z are the stress in the Y direction and the Z direction, F_y and F_z are the contact force in the Y and Z direction of the force. Considering the sensor is a thin film, the stress of the Y direction is mainly affected by the sensor so that we can ignore the stress of the Z direction in the next calculation. Therefore, the stress of any point (y, z) in this cross section can be expressed as

$$\sigma = \frac{2y^2}{\pi(y^2 + z^2)^2} yF_y \quad (3)$$

However, the sensor has a certain size, so the X direction is not infinite. Considering the influence of the X direction stress on the sensor, the stress of any point (x, y, z) in the elastic layer can be expressed as

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