A Solid-liquid Composite Flexible Bionic Tactile Sensor for Dexterous Hands

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Abstract—The sense of touch is fundamental to grasping and manipulating objects. Disabled prosthetic hands and robot dexterous hands need tactile sensors to provide tactile information to ensure that when grasping objects, the object will not be broken because the grasping force is too large, and the object will not slide because the grasping force is too small. At present, some tactile sensors have complex structures, high production costs, and are not easy to integrate. In this paper, a novel biomimetic 3D tactile sensor based on magnetic field is proposed. Most parts can be 3D printed, simple to manufacture, can measure three-dimensional forces, and can be easily integrated into prosthetic hands and robotic hands. Through experimental tests, the designed tactile sensor has a wide measuring range, can detect 15N normal force and ±6N tangential force, and has a small lag error, which can improve the tactile perception ability of the manipulator when grasping objects.

Index Terms—Bionic 3D tactile sensor, magnetic field, flexible three-dimensional force sensor.

I. INTRODUCTION

T ouch is one of the main ways that organisms perceive the information of the surrounding environment. For example, when we humans grasp objects, we can perceive the shape, quality, texture, stiffness and other information of objects through a large number of tactile receptors in the skin of our hands. Similarly, tactile perception is an important factor in the robot's contact with the external object circumstances. Tactile sensors have played a vital role in tactile perception of intelligent robots, prosthetic hands for disabled people, human-computer interaction, etc. [1-2].

With the research progress of new materials and tactile sensors, tactile sensors based on various conduction mechanisms such as resistance [3-5], capacitance [6-8], piezoelectricity [9-12], and optics [13-16] have been developed. Y. Liu et al. proposed a flexible capacitive tactile sensor that can measure three-dimensional forces. The cross bar PDMS wall and cylindrical array are used as dielectric layer sensing elements. When there is an external force, the capacitance values of the four capacitors will change, thus realizing the recognition of external forces in different directions [6]. M. A. Abd et al. proposed a new type of highly stretchable liquid metal tactile sensor, which integrated in the

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fingertips of prosthetic hands can detect and prevent the grasped objects from sliding in real time, and distinguish different surfaces with very high accuracy [22].

The above four types of sensors still have certain limitations in practical applications. Magnetic field-based sensors [17-21] are rapidly developing towards high sensitivity, high resolution and low power consumption. Using the magnetic field detection principle to perceive the deformation of flexible elastomer and infer the threedimensional force from the deformation has become an effective method to realize tactile perception. T. P. Tomo et al. proposed a distributed flexible force sensor structure, uSkin, which can reduce the interference of the three-axis force measurement components, accelerate the readout efficiency, reduce the size of the structure, and require few wires, can recognize the shape of the object [18].

In daily life, human hands can grasp and manipulate objects of various shapes and sizes, because the rich touch receptors in the finger skin can sense the three-dimensional force of contact and can adjust the grasping force of the finger to ensure safe grasp and operation. According to the structure and tactile sensing mechanism of human fingertip skin, Hall effect and magnetic field detection principle, we proposed a modular fingertip flexible magnetic field bionic tactile sensor. The sensor can detect the three-dimensional contact force. The use of solid-liquid composite form can not only increase the flexibility of the sensor, but also reduce the crosstalk of measuring the three-dimensional contact force compared with the solid flexible medium. The external dimensions and flexible structure of the designed tactile sensor and the finger are approximate, which is easy to be integrated into the prosthetic hands of the disabled and the multi-finger-smart hands of intelligent robots, and can provide powerful tactile perception for the disabled and intelligent robots.

The main contributions of the work are the following:

1) A new modular solid-liquid compound flexible magnetic field bionic tactile sensor was designed to simulate human hand skin, which has a large range of force measurement and high precision.

2) The designed bionic tactile sensor is calibrated and tested. It is integrated into the robot hand to accurately detect the three-dimensional contact force in real time, which can assist in grasping objects.

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Fig. 1. Structure diagram of the sensor.

II. TACTILE SENSOR DESIGN

A. Tactile Sensor Structure Design

We modeled the skin structure of human hand and designed a modular fingertip flexible magnetic field bionic tactile sensor. Fig. 1 is the structure of each part of the sensor, and the overall shape is similar to the fingertip of our human fingers. The sensor includes: silicone skin, PCB with 3D Hall sensor chip, cylindrical permanent magnet, insulating liquid, finger bone, pressure plate, etc. Thin flexible skin, permanent magnet, PCB and insulating liquid are the epidermis layer, touch receptor and flexible tissue of bionic human hand skin respectively.

The role of the pressure plate is to fix the thin flexible skin to the finger bone, so that the thin flexible skin and the finger bone can form a cavity, which is used to fill the insulating liquid. The cylindrical permanent magnet is attached to the thin flexible skin and acts as a magnetic source. At the same time, the PCB equipped with 3D Hall sensor chip is fixed on the rigid finger bone to detect the 3D magnetic field density. The insulator liquid is injected into the inner cavity of the thin flexible skin through a hole at the base of the finger bone, filling between the thin flexible skin and the finger bone, which provides a flexible environment, thereby increasing the flexibility.

B. Working Principle

The working principle is as follows: when the tactile sensor contacts the object in the external environment, the thin and flexible skin will be deformed under the force, which will drive the displacement of the small cylindrical permanent magnet, and the spatial magnetic field inside the sensor will also change; The change information of the spatial magnetic field density is detected by the 3D Hall sensor chip on the PCB. Then, microcontroller is used to collect the magnetic field density change data, analyze and process the magnetic field change information, and find the mapping relationship between the three-dimensional magnetic field density and the three-dimensional force, so that the tactile information such as the contact three-dimensional force can be detected.

Fig. 2 shows the way and principle of tactile sensor to perceive three-dimensional force. When there is a normal force, the thin flexible skin will be deformed along the Z-axis, which will drive the magnetic steel to produce displacement in the vertical direction, and the space magnetic field will change. When the tangential force is applied, the thin flexible



Fig. 2. Schematic diagram of magnetic field variation of sensor subjected to normal and tangential forces

skin will be deformed along the XY-axis direction, so that the magnetic steel will be displaced in the XY-axis direction, and the space magnetic field will change. Therefore, the three-dimensional contact force can be detected.

III. TACTILE SENSOR MAKING

A. Permanent Magnet Selection

Fig. 3 (a) is a schematic diagram of the internal construction of the tactile sensor, where H is the thickness of the permanent magnet, D is the diameter of the magnet, L is the horizontal distance between the four magnets, and h is the distance between the permanent magnet and the threedimensional Hall sensor chip. The overall structure size of the tactile sensor mainly depends on the model size of the permanent magnet, parameters L and h. Axially magnetized cylindrical NdFeB permanent magnet is adopted. Four types of thickness H=1mm and diameter D=2,3,4,5mm were selected for comparative analysis, and the change data of normal magnetic field density with normal distance were respectively measured and recorded. The change curve drawn is shown in Figure 3(b). As shown in Table 1, h_{max} and h_{min} that can be selected by the four permanent magnets are analyzed according to the change curve. The larger the diameter of the permanent magnet, the larger the h_{max} and h_{min} that can be selected.



Fig. 3. (a) The internal structure of the tactile sensor (b) Magnetic field density in the z-axis direction for four types of permanent magnets with thickness H=1mm and diameter D=2,3,4,5 mm

TABLE I The Selection Range of Distance h

Magnet diameter	2mm	3mm	4mm	5mm
h _{max}	5	6	7	9
h _{min}	1.6	1.8	2	2.8

Therefore, through the measurement of the magnetic field, it can be known that the triaxial displacement d(x, y, z) can be obtained through the triaxial magnetic field $B(B_x, B_y, B_z)$, and the contact three-dimensional force can be obtained. Be aimed at accurately calculate the magnetic field of permanent magnets, it is necessary to carry out numerical calculation of multiple integration, and the parameters are required to be accurate. For axially magnetized cylindrical permanent magnets, the axial magnetic field can be derived:

$$B(z) = \frac{\mu_0 M}{2} \left(\frac{z+H}{\sqrt{(z+H)^2 + \left(\frac{D}{2}\right)^2}} - \frac{z}{\sqrt{z^2 + \left(\frac{D}{2}\right)^2}} \right)$$
(1)

where, μ_0 is the relative permeability, M is the strength of the permanent magnet, and z is the space from the polar surface on the z axis. As can be seen from Equation (1), the magnetic field strength of a small-sized permanent magnet decreases rapidly. When it is so small that it cannot be distinguished from the environmental magnetic field, the measurement range of spatial three-dimensional force will be limited. However, the spatial gradient is much larger and the measurement sensitivity can be greater, while the opposite is true for large permanent magnets.

Analyzing the experience of relevant experiments, larger or stronger permanent magnets can improve the signal-to-noise ratio (SNR), but will lead to a smaller range for detecting the three-dimensional force of contact. Considering the structural size of the sensor and the Z-axis magnetic field density gradient of four kinds of diameter permanent magnets, a cylindrical permanent magnet with a diameter of 3mm and a height of 1mm is selected as the magnetic source of the tactile sensor.

B. h and Flexible Skin Hardness Selection

The tactile sensor adopts a flexible medium of solid-liquid composite which will compress and deform under force. Should select a suitable distance h between the permanent magnet and the chip and the hardness of thin flexible skin.

A smaller distance h can improve the signal-to-noise ratio, however, the physical displacement of the sensor is limited, thus limiting the range. The appropriate spacing h needs to be selected to meet the relatively high sensitivity, while the maximum displacement position is constrained by the magnetic field density to avoid three-dimensional magnetic sensing chip saturation. In the previous section, selected a permanent magnet with a diameter of 3mm as the magnetic source. According to the magnetic field change curve in Fig. 3 (b) and the size of the sensor, the distance h=4mm was selected.

Thin flexible skin is made of silicone material. The stiffer elasticity allows for a larger range of force. However, an external force causes the permanent magnet to move less than the soft elastomer. This suggests that greater hardness will reduce changes in the magnetic signal, thus reducing the sensitivity. For the silicone elastic medium of the same hardness, the smaller the distance h, the more sensitive it is to contact external forces. For the same distance h, the greater the hardness of the silicone elastic medium, the lower the sensitivity to external forces. When the silicone hardness is lower and the distance h is smaller, the 3D Hall sensor chip is easier to reach saturation (Z-axis measurement range - $26443.776\mu T \sim 26442.969\mu T$, XY-axis measurement range - $16416.768\mu T \sim 16416.267\mu T$). Considering that the size of the tactile sensor should be similar to the fingertip size of the robot bionic manipulator, the sensitivity and the ability of the sensor to withstand the overload force, the distance h=4mm is proposed to be selected, and the hardness of the thin flexible silicone skin is 15A.

C. Tactile Array Layout

The four permanent magnets are arranged in a planar array. To determine the distance L between permanent magnets, it is necessary to know the magnetic field distribution in the XY plane of the permanent magnets. That is, should avoid the initial reading of the 3D Hall sensor chip being too large, otherwise the 3D Hall sensor chip is easy to reach saturation, limiting the range of detecting the three-dimensional contact force. The permanent magnet is placed on the Z-axis of the three-axis micro-moving platform, and the three-dimensional Hall sensor chip is fixed on the Y-axis, so that the separation of the two is 4mm, and the three-dimensional Hall sensor chip is moved left and right along the Y direction, the movement range is -10~10mm.

The results in Fig. 4 show that moving the permanent magnet along the Y-axis has little effect on the X-axis magnetic field density B_x . Since in the initial state, the permanent magnet is directly above the three-dimensional Hall sensor chip, theoretically $B_x=B_y=0$, and the magnetic field density of the XY-axis is much weaker than that of the Z-axis, so the mutual influence of adjacent permanent magnets on the Z axis should be minimized. This is because the sensor needs to get the ΔB_i (i = x, y, z). According to the Fig. 4, when the distance from the central axis of permanent magnets is 6mm, B_z is relatively small, then choose the distance between permanent magnets is 6mm.



Fig. 4. Magnetic field distribution of permanent magnet when h=4mm.



Fig. 5. (a) Signal acquisition system (b) circuit schematic diagram of PCB (c) 3D rendering diagram of PCB (d) physical diagram of PCB.

D. Sensor Parts Production and Assembly

As shown in Fig.5 (a), the specific scheme is that the sensor array sends the collected 3D magnetic field density data to the signal acquisition and processing module based on STM32 through the IIC bus, and then sends the data to the upper computer through the rear serial port for analysis and display. MLX90393 is selected as the 3D Hall sensor chip. Each chip can output 3D magnetic field density data and real-time temperature data. It has a 7-bit I2C address, and the last 2 data bits can be configured by connecting the A0, A1 pins of the chip to a power supply or grounding. Thus, the IIC bus can be mounted to receive four chips. Therefore, the entire tactile sensor has 4 wires (VDD, VSS, SCL and SDA) to transmit 12 (4×3) measurements. Four MLX90393 chips are arranged in a 2×2 matrix. The circuit schematic design, three-dimensional rendering of the circuit board and physical drawings are shown in Fig. 5 (b, c, d).

The thin flexible skin of the sensor is made from AB silicone, and the hardness chosen is 15A; the finger bone, pressure plate and sealing cover are 3D printed with photosensitive resin materials; the insulating liquid selects



Fig. 6. Sensor parts production and assembly process.

dimethyl silicone oil; and copper fixing screws are used to avoid interference with the magnetic field. The specific production and assembly process is shown in Fig. 6. Mix AB silica gel at a ratio of 1:1 and stir thoroughly, put it in the mold for a few minutes, wait for the silicone to cure and take it out. Glue four permanent magnets onto the silicone skin. The prepared signal acquisition circuit PCB board is fixed on the finger bone, and then the silicone skin is fitted on the finger bone and fixed through the pressure plate. The insulating liquid is then injected through the injection hole into the thin, flexible skin and the cavity formed by the finger bone. Finally, the silicone sealing plug is installed in the injection hole and fixed through the sealing gland.

IV. SENSOR CALIBRATION AND EXPERIMENT

A. Sensor calibration

As shown in Fig. 7, the calibration platform of the tactile sensor is built, which includes a three-dimensional micromotion platform, a reference force sensor, a fixed support, and a 30° inclination bevel. The sensor can be fixed to a 3D microplatform with a fixed bracket, which provides movement of the XYZ-axis. The force sensor is used as a reference sensor. The inclined plane of 30° inclination is mainly used to apply normal and tangential forces to the tactile sensor at the same time, and the actual applied reference three-dimensional force $F_I(I = X, Y, Z)$ can be obtained from formula (2). The signal acquisition circuit PCB measures the 3D magnetic field density, records the data of the reference force sensor, and establishes the calibration data set to calibrate the 3D force output of the sensor.

$$\begin{cases} F_{X(Y)} = F \times \sin \alpha \\ F_Z = F \times \cos \alpha \end{cases}$$
(2)

Because the relationship between the change of magnetic field density and three-dimensional force is highly nonlinear, and the complex relationship can be expressed by the following function:

 $S_i = f(B_{x1}, B_{y1}, B_{z1}, \cdots, B_{x4}, B_{y4}, B_{z4}) \quad (i = x, y, z) \quad (3)$

A large amount of calibration data was collected by applying only normal force (0~15N) and simultaneously applying normal force and tangential force (-6N~6N) to the tactile sensor, and a calibration data set was established. The BP artificial neural network is used to predict the highly nonlinear relationship between the magnetic field density and the three-dimensional force, so that the contact three-dimensional force can be computed according to the measured three-dimensional magnetic field data.



Fig.7. Sensor calibration platform.

B. Sensor Performance Test Experiment

To verify the accuracy of the calibration a series of normal and tangential forces are imposed to the sensor, the output 3D force data of the sensor is collected, and the data of the reference force sensor is recorded at the same time. As shown in Fig. 8,the errors of the three-dimensional contact force (S_x , S_y , S_z) output by the tactile sensor after calibration are very small. It can be seen from Figure 8 (a) that when only the normal force is applied, the tangential force change is almost negligible, indicating that the crosstalk of the threedimensional force is small.

The designed sensor adopts array layout to normalize and visualize the magnetic field density data of each 3D Hall



Fig. 8. (a) Normal force test results for Z-axis. (b) Shear force test results for X-axis. (c) Shear force test results for Y-axis.



Fig. 9. (a) 5N normal force. (b) 10N normal force. (c) 3N shear force, 5.2N normal force. (d) 4N shear force, 6.9N normal force.



Fig. 10. Hysteresis test of sensor.

sensor chip when the tactile sensor is under stress. Only 5N and 10N normal forces are applied in the direction of Z-axis, while 3N shear force and 5.2N normal force are imposed in the direction of X and Z axis respectively, and 4N shear force and 6.9N normal force are applied in the direction of Y and Z axis respectively, these results are shown in Fig. 9. The figure shows that the output of the four chips is not consistent, which is because the production process did not make the four permanent magnets completely symmetrical distribution.

The hysteresis curve during the loading and unloading process is shown in Fig. 10. It is calculated that the hysteresis error of force sensor is about 3% in the Z-axis direction. The hysteresis results were 2.9% in the X-axis and 2.7% in the Y-axis, which verify that the flexible 3D force-tactile sensor has a small hysteresis error.

C. Sensor Application Experiment

The designed three-dimensional contact force sensor can be applied to prosthetic hands of the disabled and robot gripper. In this paper, the robot is used as the carrier to carry out the experiment of auxiliary grasping objects.

The sensor is attached to a robotic hand that can grasp most objects in everyday life, and this experiment takes the fragile strawberry as an example. Experiment process: first let the manipulator open, then the manipulator slowly closed to grasp a small strawberry and hold it for some time, and finally the manipulator opened to release the strawberry. In the process of the experiment, the tactile sensor collected the three-dimensional contact force in real time, and the results were shown in Figure 11. When the strawberry was held, the sensor detected a 1.5N normal force and 0.5N tangential force. After the robot released the strawberry, the threedimensional



Fig. 11. Assisted grasping experiment. Tactile sensor is attached to a robotic hand to grasp a strawberry.

contact force quickly returned to the initial value, indicating that the sensor has good repeatability. The above test show that the sensor has a good ability to detect the threedimensional contact force in the grasp process.

V. CONCLUSIONS AND FUTURE WORK

Based on the structure and tactile sensing mechanism of human fingertip skin, a new modular bionic tactile sensor is proposed based on Hall effect and magnetic field detection principle. The designed sensor has a flexible structure like a human fingertip, which can detect the three-dimensional contact force, and is simple to manufacture, easy to miniaturize and low cost. The use of solid-liquid composite form can not only increase the flexibility of the sensor, but also reduce the crosstalk of measuring the three-dimensional contact force compared with the solid flexible medium. BP neural network is used for correcting sensors, and carried out performance tests and auxiliary grasping object experiments, which proves that the sensor we designed has small hysteresis error. The designed sensor has a wide measuring range and can detect 15N normal force and \pm 6N shear force.

The tactile sensor designed can be easily integrated into the prosthetic hand of the disabled person and the multi-fingersmart hand of the intelligent humanoid robot. It can realize real-time detection of the three-dimensional contact force when grasping objects, ensure the safety and stability of the grasping operation, and provide the disabled person and the intelligent humanoid robot with strong tactile perception. At the same time, our fingertip tactile sensor adopts modular design, and in the future, we can design a tactile sensor suitable for finger joints and palms by changing the shape structure, giving prosthetic hands and dexterous hands allround tactile perception.

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