Design, fabrication and test of a thin and low-cost flexible force sensor

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Tactile forces are important parameters especially in the biomedical field. In this paper, a thin and flexible tactile force sensor is proposed based on the piezoresistivity of conductive rubber. The force sensor can be fabricated by a cheap manufacturing process. The design and fabrication processes of the force sensor including the measurement principle, the structure design and the fabrication procedures are described. In order to investigate the characteristics of the sensor, experiments are carried out. The design of the test bench, experiment arrangement and the experiment process are also described. The results of the experiments verify the effectiveness of the force sensor.

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1. Introduction

Tactile forces are important parameters in some biomedical and robotics applications [1, 2]. There are a variety of ways to sense the tactile force between contacting objects, for instance, human and the external environment. But some applications demand tactile force sensors have characteristics such as flexibility and thin thickness. Flexible tactile force sensors are pervasively used in these applications. This is due to that flexible tactile force sensors exhibit some good characteristics suitable for this function. The flexible tactile force sensors not only have good flexibility but also can be trimmed to any shape to fit the desired measurement system. Characteristics of a tactile force sensor such as ease of use, long lifetime and low cost are crucial influence factors to the application of the sensor.

Although there are some flexible tactile force sensors such as the FlexiForce the product of the Tekscan Corporation are available in market, they are not gotten easily in the mainland of china and the price is high at the same time. In this paper, a thin flexible tactile force sensor is designed, fabricated and tested. The force sensor is meant to carry out the qualitative measurement in the biomedical and robotics field. The manufacturing process is very easy to realize and the cost is low.

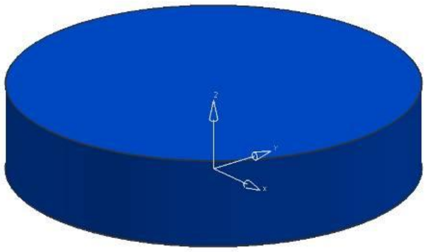
In this paper, the measurement principle of the designed force sensor is stated at first. Then the structure design and the manufacturing process are described in detail. To investigate the performance of the sensor, a test bench is designed and the process of the test experiment is stated. At last, some performance parameters of the force sensor are calculated by the data gained from the test experiments.

The result of the test experiment shows the force sensor has good characteristics in both static and dynamic tests. The performance of the force sensor verifies the usability of the force sensor in the tactile force qualitative measurement applications. The fabrication procedure is simple and the cost of the fabrication is low.

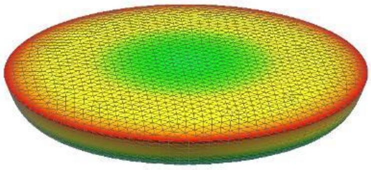
2. The measurement principle of the sensor

The piezoresistivity of some materials is useful in the design of the pressure and force sensors and transducers [3, 4]. This characteristic guarantees the sensors that are made of the piezoresistive material have the characteristics such as simple structure and large bearing capability. Conductive rubber is a kind of piezoresistive material. It can be made by adding a certain amount of conductive particles and semiconducting particles into the silicon rubber and to reach the uniform mixing state [5, 6].

In this paper, a sheet of conductive rubber with piezoresistivity in round shape is used to design the sensing cell. The sensing cell will be compressed and deform when an external normal force is exerted on it in the axial direction, as shown in Fig.1.



(a) Original state of a sensing cell



(b) Deformation under an external force

Fig. 1 The schematic diagram of detecting principle (not to scale)

The sensing cell will deform in the axial direction when an external normal force applies to it in the axial direction. This will induce the volume compression of the sensing cell. Then the electronic number in unit volume of the sensing cell increase. The increase of the electronic number results in the decrease of the electrical resistivity of sensing cell [7]. Electrical resistivity is used to express the attribute of preventing the current in the resistance of sensing cell. According to the Ohm law, the resistance of sensing cell is in direct proportion to the electrical resistivity. In other words, the sensing cell will exhibit a continuous decrease in resistance when an increasing force applies to it.

When the force sensor is integrated into a measuring electrical interface the variation of the resistance of the force sensor will convert into the variation of voltage of the measurement system. Thus a simple force-to-voltage conversion is built. By observation and analysis the output voltage variation of the measuring electrical interface, the input force applying to the force sensor could be concluded. The force sensor is suitable for the qualitative measuring instead of the precision tactile force measurement because of the properties of the conductive rubber [8].

3. The structure and fabrication of the sensor

The design structure of the force sensor based on the measurement principle stated in the section 2 is shown in Fig.2.

The flexible tactile force sensor has a sandwich structure. The flexible tactile force sensor consists of a sensing cell and two external layers beside the sensing cell. A sheet of circular conductive rubber is used to make the sensing cell. The sensing cell that is used to sense the magnitude of external force and convert it into the output of resistance is the key element in this sensor. The external layers are the substrate of the sensor and protect internal structure of the sensor avoiding ruin from the exterior environment. The external layers are composed of the PET (Polyethylene Terephthalate) films.

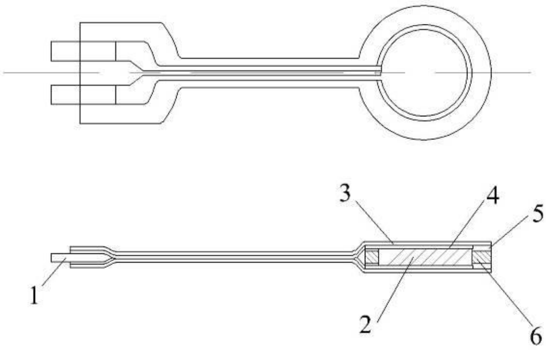


Fig.2 Cross-sectional diagram of force sensor (not to scale)
1-pin connector; 2-sensing cell; 3-external layer; 4- electrode; 5-adhesive; 6-rubber ring

A rubber ring is placed between two external layers. The rubber ring is used to locate and fix the sensing cell to ensure the alignment of the sensing cell and electrodes in the process of the measurement. The rubber ring and the external layers are bonded together by adhesive.

On each layer, a conductive material (silver) is used to print the electrode with special designed shape by the screen printing process. Electrode extends from the sensing cell to the connectors at the other end of the sensor, forming the conductive leads. The force sensors are terminated with two pin connectors, which allow them to be incorporated into a measurement circuit. The signal of resistance variation of the sensor will be delivered to the measurement circuit by the electrode and the pin connectors.

The force sensor has a simple and compact structure. The fabrication process of the force sensor is easy to realize at the same time. The screen printing process can completely realize the structure described before. The print of electrode on the external layer is the key process in the sensor fabrication. Common procedure can be explained in the following steps:

i. PET (Polyethylene Terephthalate) films are prepared at first. They should be trimmed into the designed shape and the surface that will be used to print the electrode should be conducted corona treatment to increase the adhesion between the printed electrode and the substrate before the screen printing is processed.
ii. Printed layouts are drawn and designed.
iii. Silver electrodes are printed on the external layers and another layer of carbon follows on the interface of the sensing cell and electrode to prevent the chemical reaction between the conductive rubber and the silver electrode.
iv. Two external layers with printed electrode and a sheet of circular conductive rubber and a soft rubber ring are assembled to form the force sensor. The conductive rubber and electrodes must be placed in alignment. The position deviation will degrade the performance of the sensor.
v. Adhesive is then used to laminate the two layers of substrate together to form the force sensor. It is the key process in construction of the force sensor. Good contact of the sensing cell and electrode will guarantee the good performance of the force sensor. To a great extent, it will affect the behavior of the force sensor.
vi. Two staked pin connectors are clamped on two external

layers respectively by a crimping tool.

The length of the force sensor is 45mm, the maximum width and the maximum thickness of the sensor are 15mm and 1mm respectively. The circle surface on top of the conductive rubber defines the active sensing area of the force sensor. The active sensing area is about a 5mm diameter circle at the end of the sensor.

A force sensor is fabricated out according to the procedure stated above as shown in Fig.3. The manufacturing cost of each force sensor is about 5 $. The cost will get further lower if more force sensors are fabricated.

Fig.3 Picture of the force sensor

4. Test experiments

To investigate the performance of the force sensor, an experiment device is built according to Fig.4. A force sensor is placed on the test bench without any bend because the bend may induce the resistance drift of the sensor. An aluminum rod with a 5mm diameter cylinder is used to actuate the force sensor. The weight of the aluminum rod is 10g. A series of weights are used to stack on the top of the aluminum rod to generate the required force applying to the force sensor. The center of the aluminum rod should be aligned to the center of the active area of the force sensor in the process of the experiment. A digital multimeter is connected to the two outer pins connector of the sensor to read the output resistance of the force sensor in the experimental process. The experiment scene is shown in Fig.5.

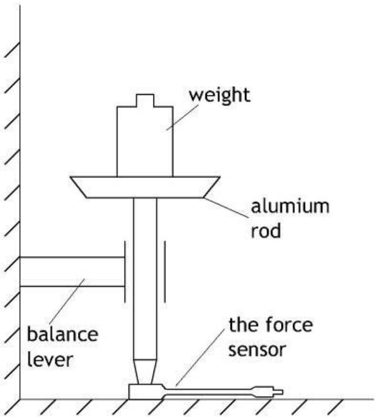


Fig.4 The schematic diagram of the experiment device (not to scale)

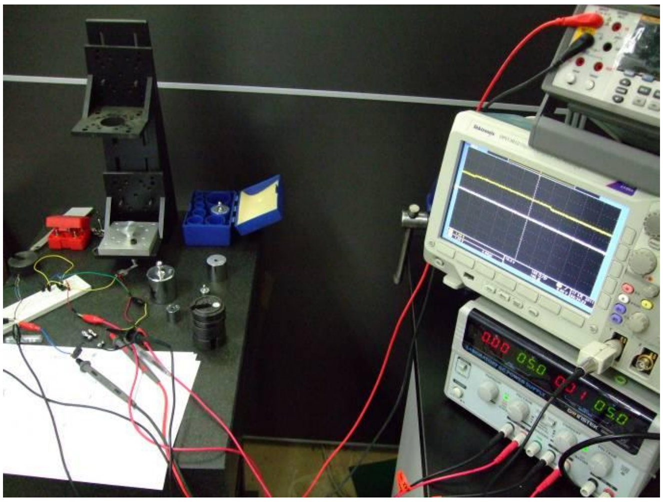


Fig.5 Picture of the experiment scene

The weight loading on the force sensor runs from 0g to 450g and back to 0g in a complete experiment procedure. The output resistance of the force sensor can be read from the multimeter and written down in a table list. The recorded data is processed by computer to get the output resistance variation curve of the force sensor versus external force applying to it.

Fig.6 shows the variation curve of the output resistance of the force sensor versus the external force applying to the force sensor. The curve of increasing force and decreasing force are given respectively. The force sensor exhibits a decrease in resistance with an increase in the force applied to it. The resistance will try to return to the initial value when the force is moved away. This characteristic of the resistance versus external force gives an overview typical response behavior of the force sensor. These data are representative of the designed force sensor in this paper. The fitting curve shown in Fig.6 is obtained by the least square method.

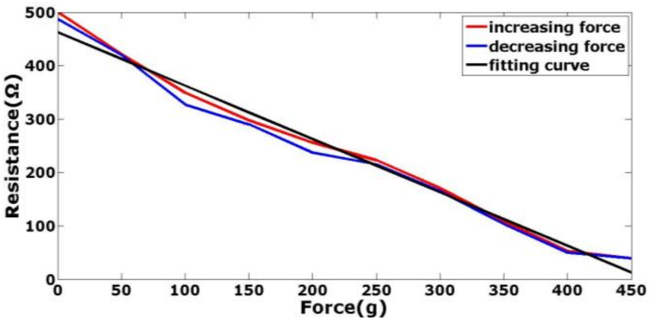


Fig.6 Sensor resistance versus external force

Because the resistance is difficult to process by the measurement circuit, the force to voltage conversion is necessary. In this paper, the force sensor is used as a current-to-voltage converter device, the schematic diagram of the circuit for the conversion is shown in Fig.7.

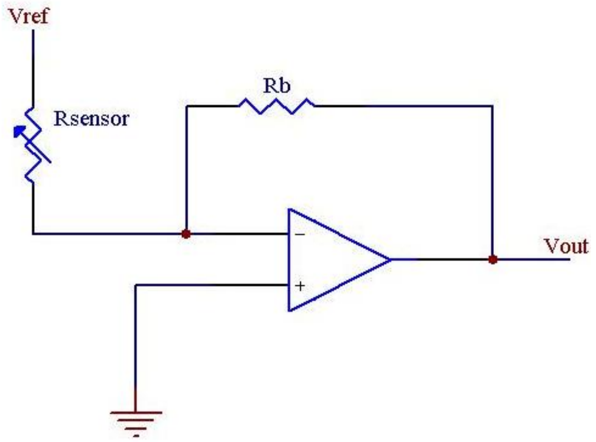


Fig.7 Schematic diagram of the circuit for the conversion

The conversion circuit is very easy to realize and the conversion relation keeps good linearity in a large range. The operational amplifier that is used in this experiment is LM358. The excitation voltage to the force sensor Vref is -5V. The bigger the excitation voltage is, the more obviously the output voltage changes. The gain control resistance Rb in the circuit is 50Ω. To a great extent, the gain control resistance decides the output gain of the conversion circuit. Changing Rb and/or Vref changes the response slope of the conversion circuit.

To investigate the dynamic performance of the force sensor another experiment is carried out. We intend to investigate the response time of the force sensor under a variable force imitating the loading and unloading a step load on the force sensor. The force changes from 0g to 500g and back to 0g in entire experiment. The recording time is 100 seconds. The capability of the force sensor to maintain the resistance output invariant under a constant force (namely drift) and the ability of the force sensor to return to the output resistance value before the force changes are other concerned problems in this experiment. An oscilloscope is used to record the output voltage of the current-to-voltage conversion circuit in the process of the experiment.

Fig.8 shows the voltage waveform in the process of a variable force applying to the force sensor in 100 seconds. The original data derived from the oscilloscope is contaminated by high frequency noise. In order to observe the voltage variation of the circuit more easily and more accurately, the original data is processed by a low pass filter. Both the original curve and the filtered curve are plotted in the Fig.8.

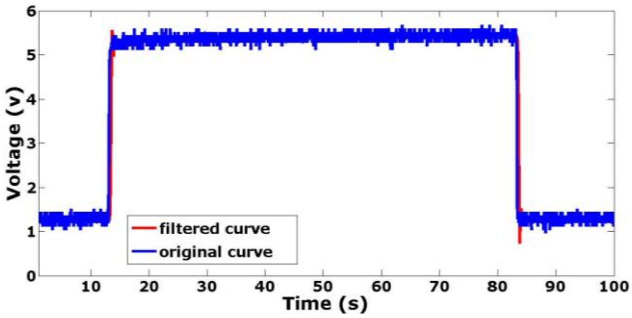


Fig.8 Circuit voltage output in the process of a variable force applying to the force sensor

5. Result and discussion

The test experiment of the force sensor is carried out according to the procedures stated in the section 4. The relationship between external force and the change of output resistance is shown in Fig.6. The performance parameters of the force sensor can be calculated by the recorded data. The linearity is -6.9% and the hysteresis is -4.89%. The sensitivity of the sensor is about -0.99Ω/g in the full measuring scope.

Fig.8 is a picture shows the voltage variation in the measurement process. It shows the voltage variation in the whole process of applying a variable force to the force sensor. The force sensor takes about 1 second to reach the stable state (95% of the peak value of the output voltage) from applying a variable force to it. The force sensor keeps relatively stable resistance output in the remaining observation time. In the steady state, the change rate of the output voltage is about 1.69mv/sec and the percent change is about 2.8%. This feature indicates that sensor’s output will change when a constant force is applied over a period of time. It takes about 1.3 seconds for the force sensor to reach the second steady output, when the force returns to the initial value before it changes. The second output voltage of the stable state is larger than the one before. The difference of the voltage is about 60mv and the percentage of deviation is about -4.74%. This fact confirms the hysteresis characteristic of the force sensor again.

These facts can be verified by the voltage-time waveform from the oscilloscope as shown in Fig.8.

These performance characteristics of the force sensor are determined by the material essentially. The conductive rubber that is used to make the sensing cell is the key influencing factor of the performance of the force sensor. The sensor’s response to the applied load shows an approximate linear relationship in certain extent as shown in Fig.6. The non-linearity in the sensor’s response and the hysteresis characteristic of the force sensor are caused mostly by the conductive mechanism of the conductive rubber.

The thickness of the conductive rubber and the structure of the electrodes do also have significant influence on the static and the dynamic performance of the force sensor. It is important to take drift into account when calibrating the sensor, so that its effects can be minimized in the practical applications.

The lifetime of the force sensor depends on the application in which it is used. The force sensors are reusable unless used in applications in which they are subjected to the ruining conditions. Some severe conditions such as against sharp edges, or shear forces should be avoided in the application of the force sensor.

6. Conclusions

The force sensor designed in this paper shows some good characteristics suitable for the application of tactile force qualitative measurement in the biomedical and robotics applications. Some key issue will be concluded as follows.

1) The designed force sensor characterized by thin thickness, light mass and convenient to use is suitable for the measurement of a tactile force between two objects.
2) The force sensor is designed based on the piezoresistivity of conductive rubber. The force sensor can be fabricated by a low manufacturing cost and the fabrication procedure is easy to realize at the same time.
3) The sensor keeps an approximate linear response to the applied load in certain extent and has a low hysteresis. When a variable force is applying to the force sensor, the force sensor shows some good dynamic performances such as fast response and output stability. All of these performance characteristics will guarantee the availability of the sensor in the applications.
4) The accuracy of the force sensor will be affected by the conductive rubber and the dimension parameters of the sensor. The manufacturing process and the assembly quality will affect the behavior of the force sensor significantly. The further investigation in materials of sensing cell and the fabrication procedure of the sensor should be carried on.

ACKNOWLEDGEMENT

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