A Novel Silicon Based Tactile Sensor on Elastic Steel Sheet for Prosthetic Hand

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Abstract. This paper focuses on developing a novel tactile sensor to be used in a prosthetic hand. A novel structure of combining an elastic steel sheet and a piezoresistive gauge is designed and fabricated by the hybrid method of the traditional machining process and the MEMS technology. Normal force loading tests by applying force from 0 to 15N and 0 to 0.1N are performed respectively to obtain the preliminary characterization of the designed sensor. The results of the testing experiments show the good linearity, sensitivity and hysteresis of the sensor. The sensor is mounted on the fingertip of a commercial prosthetic hand and covered by polydimethylsiloxane (PDMS)， which can be tested for further application.

Keywords: Tactile sensor, prosthetic hand, piezoresistive, hybrid, MEMS.

1 Introduction

Prosthetic hand is widely investigated by different research groups and at the same time commercial prostheses are also available in the market. However, most of the commercial prostheses have no or just simple on/off tactile sensor, which makes the manipulation less flexible and the function less reliable. Besides, the tactile sensors in the past researches usually have complex mechanical structures and rigorous fabrication process, which limit their further applications on the prosthetic hand.

So far, several kinds of tactile sensors have been developed based on the principles of piezoresistive [1-3], capacitive [4-5], piezoelectric [6-7], optical [8] methods and etc. The silicon based piezoresistive sensors have the high sensitivity and small sizes with well established design and fabrication techniques. However, the sensor elements (especially the silicon elements) are usually fragile [9] which decreases the reliability of the sensory system. Hence, taking advantages of the good qualities, it is meaningful to improve the robustness of the silicon based tactile sensors for their integration on prosthetic hands.

Considering the requirements of commercial prosthetic hands such as high reliability, low expense and good static force sensing ability, this paper presents an

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easily fabricated silicon piezoresistive sensor, combining with a simple mechanical structure, which performs in a reliable way under comparatively large load in addition to high sensitivity, high linearity and low hysterisis of force measurement. As the force sensing range for human hand perception is about 0.1N-10N [10], the maximum indenting load is set as 15N for the safety of potential overloading and the minimum one as 0.1N in the testing experiments.

2 Sensor Design

The sensor consists of three parts as illustrated in Fig. 1, the metal framework, the silicon gauge and the flexible printed circuit board (FPCB). The metal framework, which is U-shaped at the y-z cross section, has a 0.3mm thick square elastic sheet with two 0.9mm thick supporting braces. The sheet's width is 15mm which is designed to fit the thumb of the prosthetic hand (SJQ18-G, Danyang, China). The metal framework's material is a kind of stainless steel, 17-4ph with Young's modulus as 197Gpa and Poisson ratio as 0.3.

The metal framework has two braces used to be fixed in the thumb of the prosthetic hand, which ensures the reliable mount and the proper space between the rear surface of the steel sheet and the thumb, protecting the fragile silicon gauge. As the other two sides of the metal sheet are free, the sheet is prone to deform along the y direction.

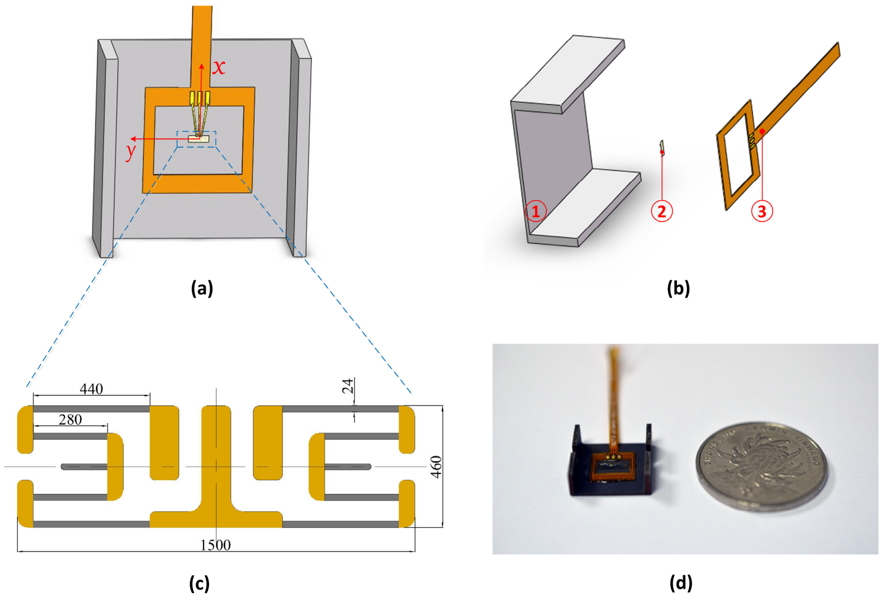

Fig. 1. Sensor structure. (a) A schematic of the sensor structure. (b) An exploded view diagram of the sensor (①the steel sheet, ②the silicon gauge, ③the FPCB). (c) Dimensional drawing of the silicon gauge. (d) Photograph of the sensor.

On the center of the rear surface of the steel sheet is the piezoresistive silicon gauge with the main mechanical features and dimensions shown in Fig. 1(c). The whole silicon gauge is symmetrical about the vertical centerline which can be divided into two independent parts with the initial resistance as 3.4 kΩ for each side. The grey parts are the silicon piezoresistors all of which align in the y direction in order to make the piezoresistors gain the maximum sensitivity. The width of the each piezoresistor is 24μm and the length has two values, 280μm and 440μm respectively. The yellow parts are the pads, among which the three one in the center are defined for welding the golden wires and the others mainly as the joints between the nearby parallel silicon piezoresistors.

In order to reserve the mounting space for the silicon gauge, the FPCB is hollow in the center with a tailor-like strip containing three leads. Thanks to the golden wires between the pads on the silicon gauge and the wire leads on the FPCB, the gauge is easily connected to the external processing circuitry.

By means of the finite element analysis (FEA) simulation tool (ANSYS Workbench 14.5), the mechanical stress in the silicon device is simulated. The stress is evaluated to prove the safety of the silicon gauge after deformation. Therefore, the force is only set at the maximum value as 15N (redundant compared to 10N) to obtain the maximum stress. As the silicon gauge is fixed on the steel sheet, its deformation is mainly up to the steel sheet deformation. Thus, the model of the simulation can completely ignore the influence of the silicon gauge and the FPCB. The model also simplifies the structure as a total flat sheet and fixes the five degrees of freedom (DOF) in two opposite edges except the DOF rotating around each edge. The force is uniformly applied on the rod indenter that contacts the surface of the sheet and transfers the force. Since the main deformation is along the y-axis direction in which the piezoresistors longitudinally align, only the y-axis normal stress is cared about. The FEA outcomes are shown in Fig. 2. On the rear surface of the strain steel, the stress is tensile when the force is applied. From Fig. 2(b), the area around the center (especially the red parts) is quite different from the regions nearby due to the singularity region in which the edge of the indenter base contacts the steel sheet. The maximum y-axis normal stress (though related to the singularity region) around the center is about 380.89 MPa which is far less than the silicon yield stress (2.8-7 GPa) [11], thus the silicon gauge is quite safe under this design.

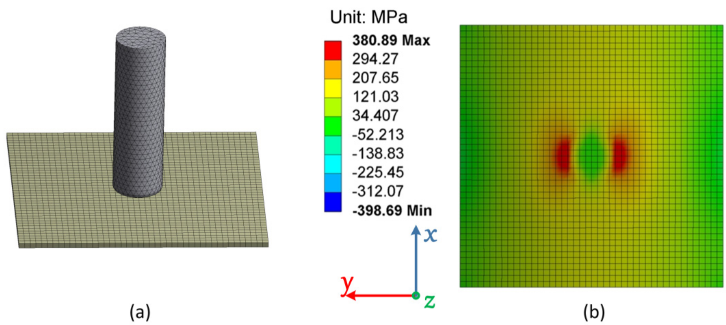

Fig. 2. FEA outcomes with an applied force of 15N. (a) The FEA model. (b) The distribution of the y-axis normal stress on the rear surface of the steel sheet.

3 Sensor Fabrication

The metal framework is grinded from a steel block before being polished to get a 0.3mm thick sheet and two 0.9mm thick braces. And the silicon gauge is fixed on the rear surface of the steel sheet by the technology of glass sintering. Around the gauge, the FPCB is glued on the surface. Using the ultrasonic bonding machine, the golden wires are connected to the FPCB and the silicon gauge respectively.

The sensing elements have been fabricated with an SOI wafer based on the dry etching technology. The SOI wafer is p-type, doped with boron with a <110> surface orientation. Fig. 3 illustrates a SEM image of the fabricated sensor.

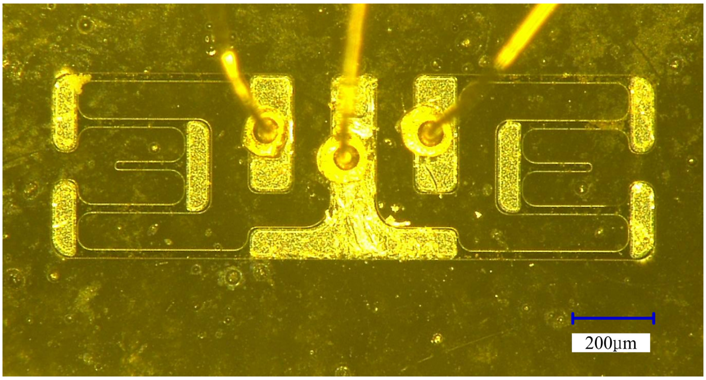

Fig. 3. SEM picture of the silicon gauge structure

4 Preliminary Characterization Experiments

In order to investigate the measuring ability of the silicon sensor, preliminary characterization experiments have been performed. The signal conditioning circuitry and the testing platform have been set up; the sensor mounting and packaging on the prosthetic hand have been tried.

4.1 Read out Electronics

A Wheatstone bridge circuit is set up for each piezoresistor (initial resistance about 3.4 kΩ) independently, which produces an output voltage proportional to the resistance change ΔR/R in the piezoresistors. In the Wheatstone bridge, there are two resistors R1, R2 with precise resistance of 3.4 kΩ and a variable resistor Rvar used to adjust the initial offset level to zero. The bridge output signal is then led to an operational amplifier (AD620, Analog Devices) with the adjustable amplifier gain A from 1 to 10000. The final output signal is measured by a data acquisition (DAQ) card (NI 6343, National Instruments) which is connected to a computer. The input voltage is Vin =5.0 V while the output voltage Vout is controlled under 5.0 V to fit the measurement range of the DAQ card. Considering a balanced bridge where R1=R2=Rvar=R, the output voltage Vout is

$$V_{out} = AV_{in} \frac{\Delta R}{4R + 2\Delta R} \approx AV_{in} \frac{\Delta R}{4R} \quad (1)$$

4.2 Experimental Set-Up

The characterization apparatus is shown in Fig. 4. It consists of a three-axial motion platform, a sensor mount platform, a link block, a three-axial force sensor, a signal conditioning electronic circuit board, a data acquisition card and a computer for data acquisition and analysis.

The three-axial force sensor (FC3D50-50N, Force China) is fixed on the three-axial motion platform (M-VP-25XA-XYZL, Newport) through a link block. And a rod indenter is also screwed into the force sensor. Thus, the indenter can move precisely in three-axial direction, by which a force can be loaded at a proper location of the designed sensor. The force value is obtained by the three-axial force sensor whose measurement range is from -50N to 50N with precision as 0.01N. The three-axial motion platform can drive the indenter at the max range of 25 mm in each direction and the lowest speed at 1 μm/s. Thus, a precise force variation can be obtained by the motion control of the platform.

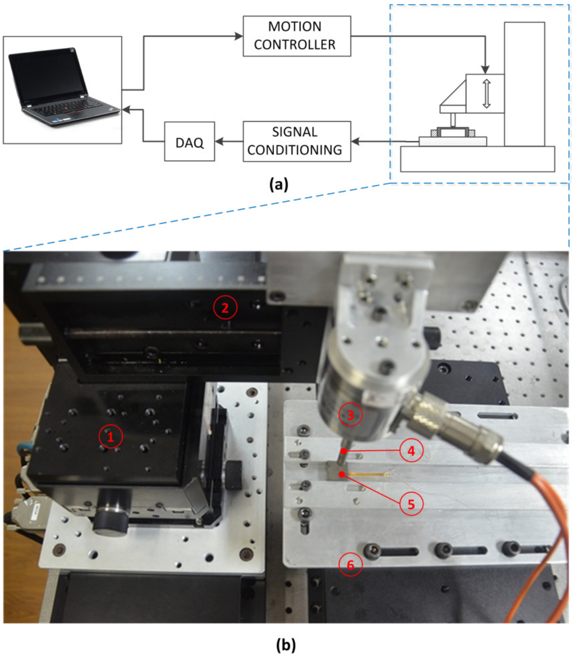

Fig. 4. (a) A schematic of the testing system; (b) Photograph of the force loading system (①the three-axial motion platform, ② the link block, ③ the three-axial force sensor, ④ the rod indenter, ⑤the designed sensor, ⑥the sensor mount platform).

The diameter of the rod indenter is 3mm. A force is loaded when the indenter contacts the surface of the steel sheet. It can be assumed that the force loaded on the metal sheet is uniformly distributed at the circle contact area.

Normal load tests will be performed to analyze the mechanical properties of the sensor. In order to get the maximum deformation of the steel sheet under the same load, the load area is confirmed to be near the center of the upper surface of the metal sheet. As both the axis and the motion direction of the indenter are perpendicular to the surface of the metal sheet, the shear force can be ignored and only the normal force is considered.

Before the loading of the force, the target position of the indenter should be determined. Firstly, the three-axial motion platform is manually driven to locate the center of the indenter base at one of the vertices of the square steel sheet and only a small offset vertically. Secondly, the motion platform is automatically driven at the displacement of 7.5 mm (half of the width of the steel sheet) in both x and y directions. Thirdly, the motion platform is automatically driven again, but only in the vertical direction, at the speed of 0.01 mm/s to load the force. The measurement value of the loading force from the three-axial force sensor can be monitored in the interface of the SignalExpress (Version 2011, National Instrument). If the force value is beyond the planned one, the motion can be aborted immediately through the motion control interface in the PC. Therefore, the automatic motion of the platform can be easily controlled to obtain a proper force value. Considering the requirements of the contact force in the human hand of grasping objects, the maximum force to load is set at 15N and 0.1N respectively.

Afterwards, the sensor is tried to be mounted on the commercial prosthetic hand for further testing experiments such as grasping tests. The inside of the two braces of the sensor is glued to the lateral sides of the thumb of the prosthetic hand. In addition, the rear side of the steel sheet keeps a normal distance from the fingertip of the thumb to protect the silicon gauge. Then a flexible layer packaging follows by using the packaging material polydimethylsiloxane (PDMS) at 10:1 of monomer to curing agent and a designed mould with the chamber shaped like a humanoid thumb. Fig. 5 shows the final image of the sensor mounted on prosthetic hand with the elastic cover.

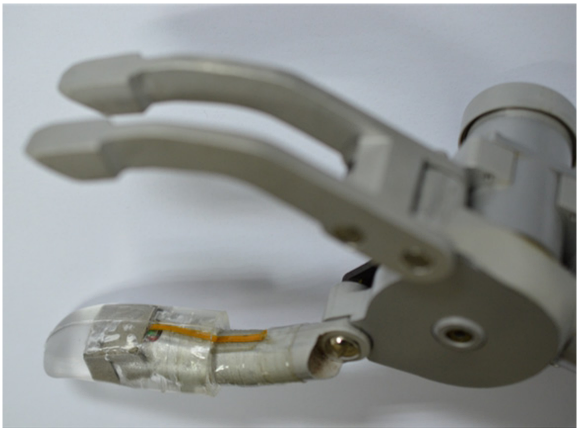

Fig. 5. Photograph of the sensor mounting and packaging on the prosthetic hand

5 Experimental Results and Discussion

The continuous normal load tests have been performed when an applied force is increasing from 0 to 15N and decreasing back to zero at a constant translational speed of 0.01mm/s along the z direction. These tests have been repeated five times to make sure the reliability of the system.

Typical sensor outputs ΔR/R in response to the force loading and unloading are plotted in Fig. 6. Using the linear regression technology, the linear fitting lines are also plotted in Fig. 6. The resulting sensitivity is $0.0047N^{-1}$ for loading and $0.0046N^{-1}$ for unloading. The coefficient that quantifies the linearity of the curve is 0.999 for both loading and unloading, very close to one, which means good linearity. The maximum hysteresis is 0.0015 happened at the zero force loading moment, which is also low compared to the sensitivity.

The set-up of the minimum normal load tests is the same as the tests mentioned above except the applied force from 0 to 0.1N. In Fig. 7, typical sensor resistance response to the force loading and unloading is plotted. There is an instant response when the applied force steps up to 0.1N or down to 0. The resistance change value to the force step is about 5Ω which is not large enough for reliable force discrimination but expected to be improved following the sensitivity improvement.

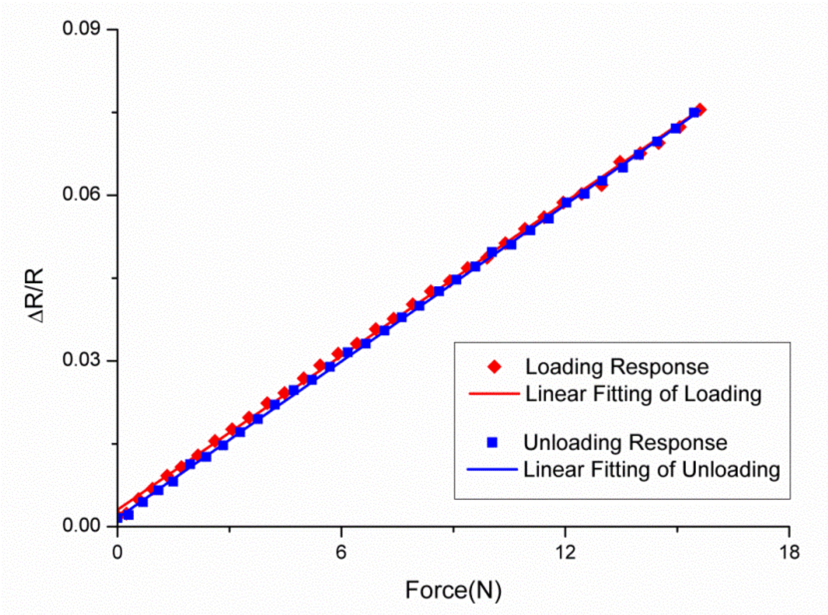

Fig. 6. Hysteresis cycle for one piezoresistive gauge. The linear fittings of loading response and unloading response are also plotted.

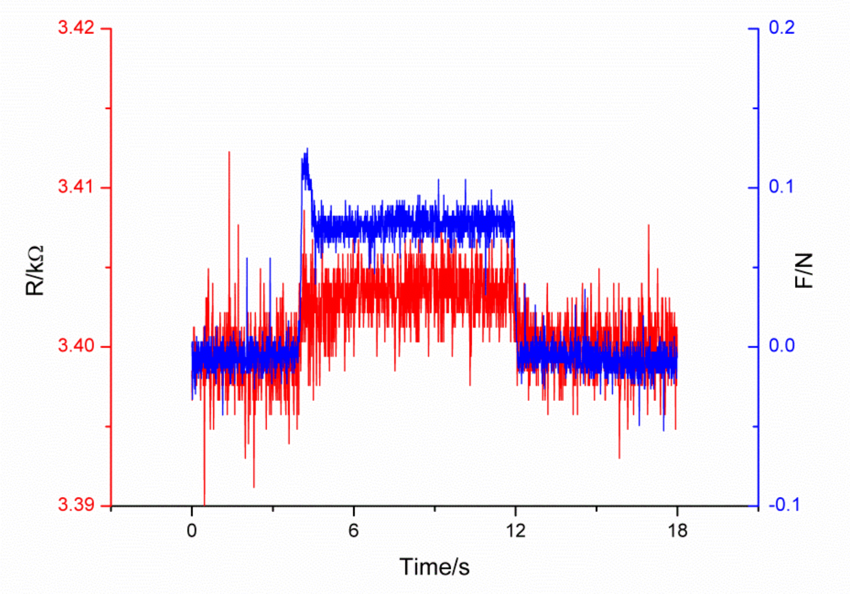

Fig. 7. Minimum load tests results with applied force as low as 0.1N

6 Conclusions and Future Work

A silicon based tactile sensor with a novel structure has been designed and fabricated. The testing experiments by indenting at the center of the steel sheet has been performed which proves the high reliability of this sensor. Meanwhile, the tests indicate the good measurement ability that the force range effectively measured is from 0.1N to 15N with the high linearity, high sensitivity and low hysteresis. In the last, the sensor is well mounted on the commercial prosthetic hand and packaged by the PDMS layer, which will be used for further application of the sensor integration on the prosthetic hand.

Future work will consist in the optimization of the geometric structure of the sensor to improve the sensitivity more and the development of the silicon gauge array integrated on the steel sheet. Moreover, the testing experiments of indenting on different regions of the steel sheet and the influence of the PDMS layer covered on the sensor will also be performed.

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