A Novel Tactile Sensing Array with Elastic Steel Frame Structure for Prosthetic Hand

Chunxin Cu, Weiting Liu(✉), Xiaodong Ruan, and Xin Fu

The State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University,
Zheda Rd. 38, Hangzhou, China
`{cxgu,liuwt,xdruan,xfu}@zju.edu.cn`

Abstract. A novel tactile sensing array based on elastic steel frame structure for prosthetic hand is proposed. The sensing units are mounted on the curving surface of a 3D printed sensor holder with five along the axial direction and four in the circumferential direction. Each sensing unit consists of a steel frame, a silicon gauge and flexible printed circuit board (FPCB). Based on the piezoresistive effect, the sensing unit can measure the normal force and the shear force along the longitudinal direction. The finite element analysis is conducted to evaluate the mechanical performance of the sensing unit. Meanwhile, the solution of detecting the resultant force is proposed.

Keywords: Tactile sensing array · Elastic steel frame · Silicon gauge · 3D print · FEA

1 Introduction

With the great demands for smart control, tactile sensor is indispensable for prosthetic hand. In common life, the modality of grasping is frequently utilized for prosthetic hand, which requires the ability of detecting normal force and shear force at the same time from the tactile sensor. Although having been widely investigated, the current tactile sensors are still far away from effective application in commercial prosthetic hand due to their complex structure, rigorous fabrication and poor stability.

So far, different tactile sensors have been developed based on several principles such as piezoresistive, capacitive, piezoelectric, optical methods [1–4] and etc. Among them, silicon based sensor fabricated by MEMS technology is favored for its high sensitivity, high stability and good compatibility with current electronic technology. In MEMS, the structures like cantilevers and beams are widely used to transmit force. For example, Beccai et al. have designed and fabricated a silicon three-axial force microsensor with a mesa located at the center of a cross-shaped beam [5]; Noda et al. have developed a tactile sensor composed of standing piezoresistive cantilevers and bridges to detect both normal and shear forces [6]. However, the silicon based sensing elements are usually fragile especially under an unexpected overload [7], which demands careful packaging design and decreases the reliability of the sensory system.

In our previous work [8], a tactile sensor with a silicon gauge fixed on a steel sheet was developed and tested with the result of good linearity, sensitivity and large force

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range. Besides, based on the hybrid method of the traditional machining process and the MEMS technology, the prototype of the previous sensor takes advantages of easy fabrication and low expense which encourages further optimization and application of the structure.

In this study, we design a tactile sensing array mounted on a curving surface. Continuing the hybrid idea, we combine the silicon gauge with the elastic steel beam and optimize the structure by adding a cuboid mesa on the steel beam which does good to shear force detection. Moreover, simulation work is conducted to evaluate the mechanical performance of the sensor unit.

2 Design and Fabrication Method

The proposed design of the tactile sensing system is shown in Fig. 1. The system consists of a sensor holder, a tactile sensing array and a flexible printed circuit board (FPCB).

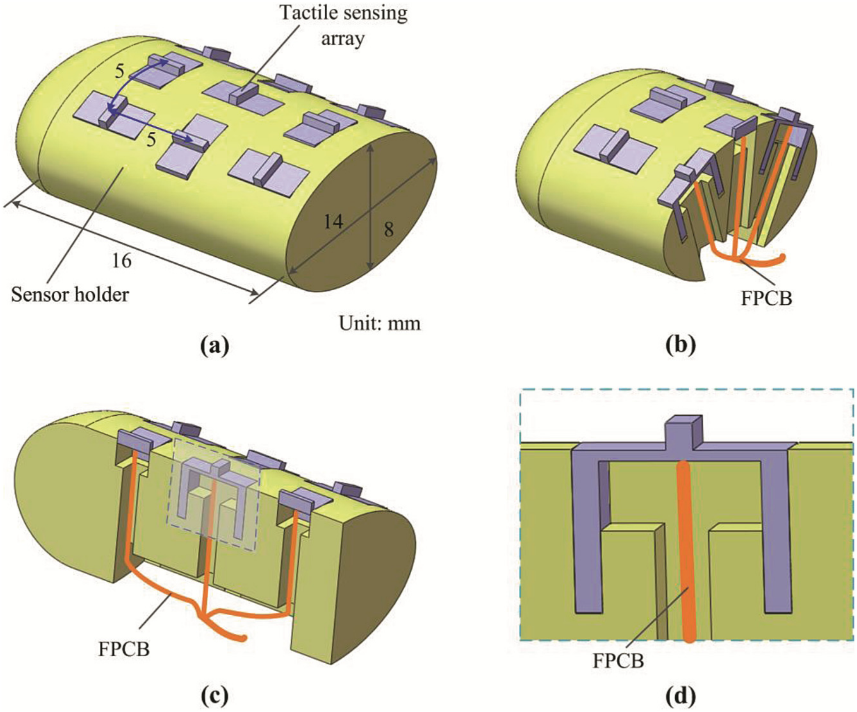
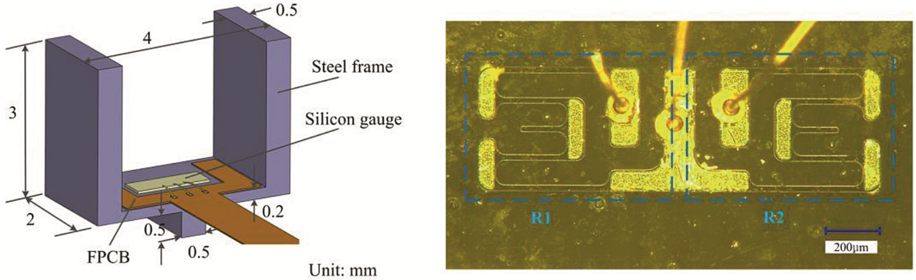


Fig. 1. Design of sensor structure. (a) Schematic of the whole sensor; (b) Cross section view of the sensor in a plane perpendicular to the axis direction of the holder; (c) Cross section view of the sensor in the vertical symmetry plane; (d) Local view of the sensing unit being fixed into the grooves of the sensor holder.

The holder is ellipse shaped in the cross section with the sizes of major axis and minor axis as 14 mm and 8 mm respectively, which shares the similar shape and dimensions of the distal phalanx of an adult's finger. On the curving surface of the holder, a 3 × 3 groove array intended for mounting the sensing array is located with both circumferential and axis spacing as 5 mm. In each groove, a channel is reserved extending to the back side of the holder to keep a path for the FPCB. Considering the relatively complex structure with the curving surface, grooves and channels, the holder is printed directly from the computer-aided design (CAD) file by the ProJet 3610 series professional 3D printer (3D System Inc.). The material of the structure is VisiJet Crystal with true plastic look, good mechanical properties and low density as 1.02 g/cm^3, which provides advantage of lightweight for tactile sensor integrated on the prosthetic hand. As shown in Fig. 1(a), there are five sensing units fixed along the axial direction and four along the circumferential direction, which is designed for detecting shear forces in both directions. The principle of shear force detecting will be discussed detailedly in the below context.



(a) (b)

Fig. 2. Design of sensing unit. (a) Schematic of sensing unit structure; (b) Microscope photograph of the silicon gauge.

Plotted in Fig. 2(a), each unit of the sensing array contains an inverted U shaped steel frame which could be divided into a beam and two supporting braces. The beam has the dimensions as 3 mm, 2 mm and 0.2 mm respectively in each direction while the supporting braces have the thickness of 0.5 mm with the height as 3 mm. On the beam, a 0.5 mm thick cuboid mesa is designed to transmit force especially the shear force. According to its modest complexity and dimensions, the whole structure is available from mature machining process using the 65 M spring steel due to its high elasticity and well machining properties. On the reverse side of the beam, a silicon gauge is fixed in the center acting as the sensing element. The silicon gauge is fabricated by MEMS processing technology and has been applied in the previous work, which shows good linearity, sensitivity and large force range. As shown in Fig. 2(b), the silicon gauge is 1.5 mm long and 0.5 mm wide which brings no difficulty to be manipulated by manual work. The whole silicon gauge can be divided into two independent parts marked as R_1 and R_2 with the initial resistance as 3.4 kΩ for each. The gauge factor G for both R_1 and R_2 is 100, which means the relationship between the resistance values change and the strain values is shown as below:

$$\begin{cases} \frac{\Delta R_1}{R_1} / \varepsilon_1 = G \\ \frac{\Delta R_2}{R_2} / \varepsilon_2 = G \end{cases} \tag{1}$$

The silicon gauge aligns along the longitudinal direction of the steel beam, which complies with the largest stretch strain inside the beam under a force load. To make sure reliable adhesion and avoid stress relaxation, the mature technology of glass sintering is adopted to mount the silicon gauge well on the reverse surface of the steel sheet, which guarantees the same deformation between the silicon gauge and the steel beam.

3 Simulation

In this study, the sensor is just evaluated on its performance under static load, which corresponds to the stable manipulation process for prosthetic hand such as grasping an object for a while. Due to the good elastic property of the spring steel and small deformation, the static analysis of the sensor structure is based on the hypothesis of linear elasticity. By means of the finite element analysis (FEA) tool (ANSYS Workbench 14.5), the mechanical behaviors of the sensor under various loading conditions are analyzed.

3.1 Under Various Force Conditions

As all sensing units have the same structure, a single unit is analyzed under the conditions that an external normal force or shear force is applied on the mesa respectively. As shown in Fig. 3(a), the sensing unit is simplified into a two-dimensional model while the bottom surfaces of two supporting braces are constrained in all degrees of freedom. The size of the finite elements meshed is 0.05 mm which provides enough computational precision for the model. The Young's modulus of the spring steel is 197 GPa with the Poisson's ratio as 0.3 used for FEA.

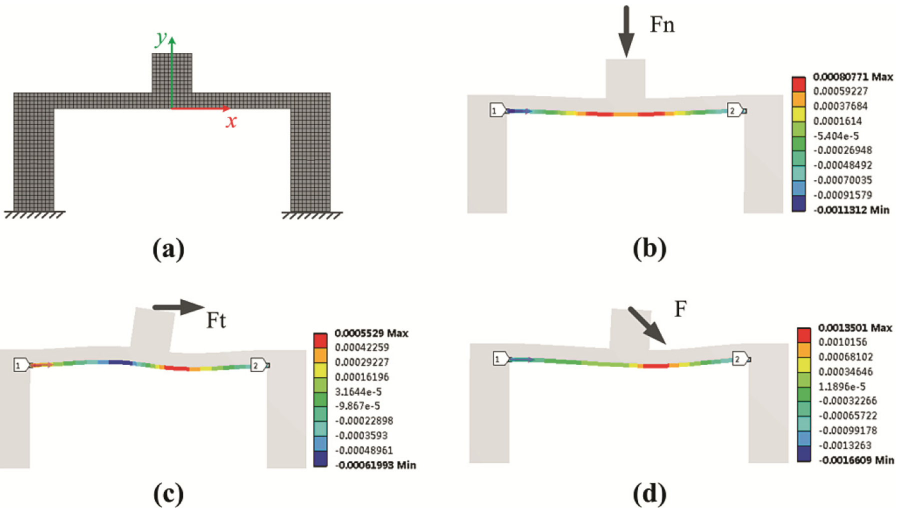


Fig. 3. Simulation results. (a) The meshed FEA model of the sensing unit; (b) X-directional normal strain distribution under a 10 N normal force; (c) X-directional normal strain distribution under a 10 N shear force; (d) X-directional normal strain distribution under a combined force with 10 N in both normal and shear directions.

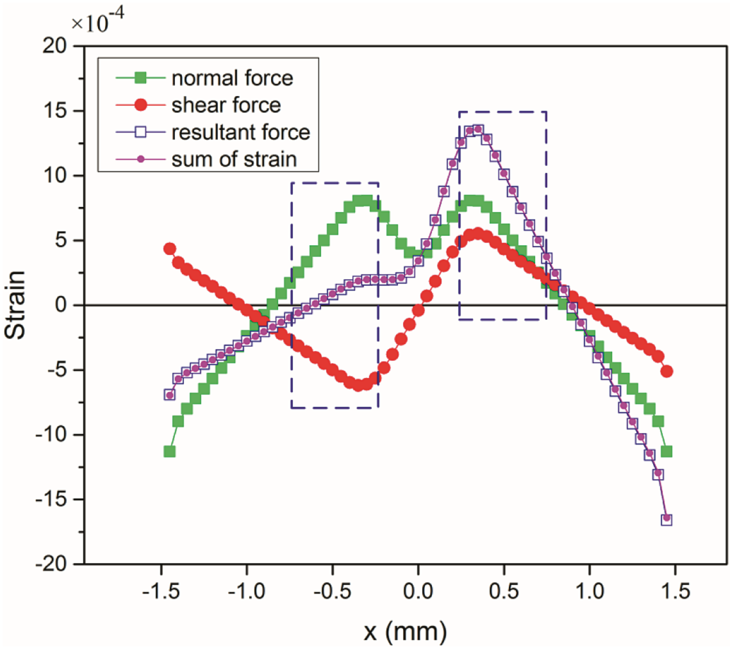


Fig. 4. Simulation results for x-directional normal strain distribution along the x-axis under various loading conditions with values set as 10 N for both normal and shear force and 10 N in two directions for the resultant force.

Due to the piezoresistive effect, the silicon gauge's resistance values linearly depend on the change of the normal strain in the longitudinal direction marked as x-direction in Fig. 3. As the force sensing range for human hand perception is within 10 N [9], the force value is set as 10 N in both normal and shear directions. Then the results under the normal, shear and resultant force loading are shown in Fig. 3(b), (c) and (d) respectively. As the silicon gauge is on the reverse side of the steel beam, only the normal strain distribution on the reverse surface is concerned. Meanwhile, the silicon gauge actually contains two independent sensing resistors as R_1 and R_2 which are located symmetrically about the axis of steel frame. Hence, R_1 and R_2 share the same value change under a single normal force and the reversal value change under a single shear force. Besides, the good elasticity of the steel beam makes it reasonable that a resultant force could be split into a single normal force and a single shear force.

In Fig. 4, the x-directional normal strain distribution along the reverse side is plotted under different force loading conditions as 10 N for both the single normal force and shear force and 10 N in both directions for the resultant force. The curve about the sum of strain is realized by adding the values from the single normal and shear force directly so that it is compared with the curve under the resultant force to further ensure the good elasticity of the sensing structure. The two blue dot rectangles are plotted to indicate the locations of the two sensing resistors R_1 and R_2 and which values belong to them.

3.2 Inverse Solution for Resultant Force

From the analysis results mentioned above, we can infer that it is possible to work out the values of a resultant force loaded on the sensing unit as long as the measurement values show good linearity in the full range. The x-directional normal strain is analyzed in the force range from 0–10 N for both normal loading and shear loading. As shown in Fig. 5, the strain values are obtained by calculating the average of strain values of those nodes disturbed in the silicon resistor's location range. It indicates that the sensing unit has good linearity in measuring both normal force and shear force with the sensitivity as $5.5 \times 10^{-4}\ \mathrm{N}^{-1}$ and $4.1 \times 10^{-4}\ \mathrm{N}^{-1}$ respectively. The relationships between the strain values and forces are shown below:

$$\begin{cases} \varepsilon_n = k_n \cdot F_n \\ \varepsilon_t = k_t \cdot F_t \end{cases} \tag{2}$$

The subscripts "*n*" and "*t*" represent for normal force and shear force respectively. Meantime, considering the symmetrical properties of the output values, the variant values of R1 and R2 could be represented as followed:

$$\begin{cases} \varepsilon_1 = \varepsilon_n + \varepsilon_t \\ \varepsilon_2 = \varepsilon_n - \varepsilon_t \end{cases} \tag{3}$$

From the Eqs. (1), (2) and (3), we can determine the normal force and shear force to form the resultant force:

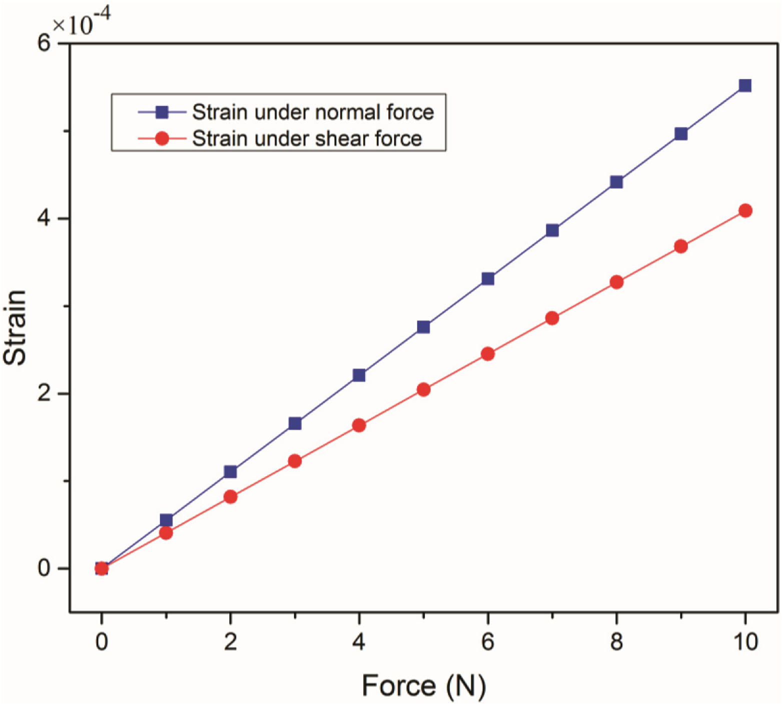


Fig. 5. Strain values change of sensing resistors in the silicon gauge under normal force and shear force.

$$\begin{cases} F_n = \dfrac{1}{2Gk_n}\left(\dfrac{\Delta R_1}{R_1} + \dfrac{\Delta R_2}{R_2}\right) \\ F_t = \dfrac{1}{2Gk_t}\left(\dfrac{\Delta R_1}{R_1} - \dfrac{\Delta R_2}{R_2}\right) \end{cases} \tag{4}$$

4 Conclusions

A tactile sensing array with novel structure composed of the silicon gauge and steel frame has been designed and the fabrication method has been proposed. The finite element analysis of the mechanical structure has been implemented, which shows good linearity and force detecting range in both normal and shear directions. In addition, the inverse solution to solve the resultant force has been obtained, which indicates the ability of detecting grip force and lift force for the sensing array when the prosthetic hand is grasping an object. However, a prototype needs to be realized and tested in a real environment in the future work.

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References

1. Büscher, G.H., Kõiva, R., Schürmann, C., Haschke, R., Ritter, H.J.: Flexible and stretchable fabric-based tactile sensor. Robot Auton. Syst. **63**, 244–252 (2015)
2. Lee, H.-K., Chung, J., Chang, S.-I., Yoon, E.: Normal and shear force measurement using a flexible polymer tactile sensor with embedded multiple capacitors. J. Microelectromech. Syst. **17**, 934–942 (2008)
3. Seminara, L., Capurro, M., Cirillo, P., Cannata, G., Valle, M.: Electromechanical characterization of piezoelectric PVDF polymer films for tactile sensors in robotics applications. Sens. Actuators, A **169**, 49–58 (2011)
4. Xie, H., Jiang, A., Wurdemann, H.A., Liu, H., Seneviratne, L.D., Althoefer, K.: Magnetic resonance-compatible tactile force sensor using fiber optics and vision sensor. IEEE Sens. J. **14**, 829–838 (2014)
5. Beccai, L., Roccella, S., Arena, A., Valvo, F., Valdastri, P., Menciassi, A., Carrozza, M.C., Dario, P.: Design and fabrication of a hybrid silicon three-axial force sensor for biomechanical applications. Sens. Actuators, A **120**, 370–382 (2005)
6. Noda, K., Hashimoto, Y., Tanaka, Y., Shimoyama, I.: MEMS on robot applications. In: International Conference on Solid-State Sensors, Actuators and Microsystems Conference, TRANSDUCERS 2009, pp. 2176–2181. IEEE (2009)
7. Yousef, H., Boukallel, M., Althoefer, K.: Tactile sensing for dexterous in-hand manipulation in robotics—a review. Sens. Actuators, A **167**, 171–187 (2011)
8. Gu, C., Liu, W., Fu, X.: A novel silicon based tactile sensor on elastic steel sheet for prosthetic hand. In: Zhang, X., Liu, H., Chen, Z., Wang, N. (eds.) ICIRA 2014, Part II. LNCS, vol. 8918, pp. 475–483. Springer, Heidelberg (2014)
9. Jones, L.A., Lederman, S.J.: Human Hand Function. Oxford University Press, London (2006)