Fabrication of a three-axial flexible tactile sensor based on polymer micromachining

*Woo-Chang Choi, *Hyun-Jun Kwon and *Jong-Ho Kim

ABSTRACT

This paper describes the design and fabrication of a flexible three-axial tactile sensor using advanced polymer micromachining technologies. The tactile sensor is comprised of sixteen micro force sensors (4 x 4) and its size being 13 mm x 18 mm. Each micro force sensor has a square membrane, and its force capacity is 30 N in the three-axial directions. The Normal and shear forces are detected by combining responses from four thin-film metal strain gauges embedded in a polyimide thin-film membrane. The optimal positions of the strain gauges are determined by the strain distribution obtained form finite element analysis (FEA). Both normal and shear forces is measured by applying forces from 0 to 0.6 N. Finally, the fabricated sensor is calibrated using the evaluation system for three-axial force sensor. The developed three-axial tactile sensor shows high linearity and low hysteresis.

Key Words : Tactile (촉각), Sensor (센서), Flexible (유연한), Polymer (폴리머), MEMS (멤스), Three-axial (3 축)

1. Introduction

Microelectromechanical systems (MEMS) have the potential to apply to integrated sensor system on robot industry. In case of robot, sensory input should be similar to or superior to the human senses in order to replace humans in dangerous or delicate circumstance. It is necessary for the tactile sensor for fingertip of robot to control and manipulate the grasping force of some objects through mechanical contact. When human’s fingertip comes into contact with an object, a contact force profile has three components: one is normal force oriented to the surface, the others are shear force oriented to the surface. Sensing and processing of these three-axial force profiles provides humans with a rich source of information about their physical environments. Especially, the shear force component is very important from a viewpoint of slip detection between fingertip and object. In addition, measuring shear force enables prediction and determination of object slip as well as estimation of static coefficient of friction [1,2].

Many researchers have developed MEMS-based tactile sensors. Some works mainly focused on silicon-based three-axial or shear force sensors using piezoresistive or capacitive principles for sensing. These devices were embedded in polymer layer to protect sensing elements [2,3]. Other groups have developed polymer-based tactile sensor that can measure only normal force [4].

The tactile sensor based on silicon substrate has basic limitations. The silicon material is mechanically brittle and rigid. Therefore it is liable to break when large deformation or external impact is applied to the sensor. In addition, it is difficult to attach sensor to bending surfaces.

In other to be used for fingertip of robot, sensors should satisfy requirements as: linearity, low hysteresis, durability, mechanical flexibility, and robustness. Polymer materials can be satisfied with the points mentioned above. Miniature polymer-based three-axial tactile sensors are able to be a solution for the fingertips of robot. In this paper, we present the design and fabrication of the polymer-based three-axial tactile sensor for the fingertips of robot. Conventional polyimide film (PI) is used for the substrate of tactile sensor. Four strain gauges
are positioned independently in order to measure the three components of applied forces through a resistance change. The fabrication is performed by polymer micromachining technology. In addition, the fabricated tactile sensor is evaluated using the equipment with three-component load cell. The developed device can be applied in robot’s fingertip as well as in other electronic applications where the keyword requirements are three-axial force measurement and flexibility.

2. Sensor design

The sensor consists of a flexible sensing structure with four strain gauges. An external force applied to the sensor can be resolved into its three components x, y, z as shown in Fig. 1. In order to obtain maximum sensitivity, regions of high stress have been identified and the dimensions and position of strain gauges have been determined accordingly.

We designed a unit of the three-axial tactile sensor as shown in Fig. 1(a). The size of the unit has 2.5 mm x 2.5 mm and the thickness of membrane is 50 µm. The thickness of membrane has been decided that the force capacity of sensor is equivalent to the maximum load for tactile sensors to be applied in artificial fingertips. The schematic diagram of the designed three-axial tactile sensor with four strain gauges (S1 ~ S4) is shown in Fig. 1(b). The position of strain gauges has been acquired from the FEA results as shown in Fig. 1(c). Four strain gauges lie on the periphery of the membrane that has maximum displacement. From the FEA results, it is clear that the strain gauges positioned at the periphery of the membrane have maximum sensitivity [5].

Fig. 1 (a) Schematic diagram of the dimension for the designed force sensor; (b) Schematic perspective view of a single tactile sensor with four strain gauges S1 ~ S4; (c) Strain distribution obtained from FEA analysis at the location along the centerline of membrane when each loading (Fz,Fx) of maximum load 0.6 N is applied respectively.

The commercial finite element program, ANSYS ver. 5.7, is used in order to design sensing element. The used material is polyimide that has elastic modulus of 3.4 GPa, ultimate stress of 190 MPa, and Poisson’s ratio of 0.33. We use the finite element model that consists of the shell element with four nodes. The supporting block of the sensing element except for membrane with thickness of 50 µm is constrained at bottom. Normal load, Fz, is applied uniformly to the upper surface (600 µm x 600 µm) of bump. Each shear load, Fx, Fy is applied uniformly to the lateral face of bump respectively.

Maximum force applied to the sensor is 0.6 N. Fig. 1(c) shows the strain distribution in the direction x at the location along centerline of membrane which has size of 750 µm x 750 µm when each maximum load is applied in three directions respectively. In case of Fz loading, the strain distribution along x-axis of membrane shows the symmetric distribution with respect to y-axis. Meanwhile, when the force, Fx, or Fy is applied to the bump, the strain distribution along the centerline indicates the asymmetric inclination with respect to origin point. In case of Fx loading, the strain distribution along the x-axis has almost zero value. Using these strain distribution values, the shape of strain gauge and its size is determined in order to maximize the sensitivity of the sensor. When a strain gauge is located around the periphery of membrane, the average strain value of strain gauge has 4500 µm in case of Fz loading. Meanwhile the average strain value is 1000 µm when Fx loading is applied. Thus the ratio of the sensitivity of Fz loading has 4.5 times over Fx loading. On the other hand, when the sensing element is subjected to three loadings, Fx, Fy and Fz simultaneously, the strain distributions are very
important in order to extract each force component signals without interference from signals of four strain. Using the strain distributions at locations of strain gauges, the solution of the decoupling method for obtaining three force components signals can be represented as follows [5].

For \( F_z \) loading, using strain gauge signal \( S_1, S_2, S_3 \), and \( S_4 \),
\[
\Delta V_{F_z} = \Delta V_{S_1} + \Delta V_{S_2} + \Delta V_{S_3} + \Delta V_{S_4}
\]
(1)

for \( F_x \) loading, using strain gauge signal \( S_1 \) and \( S_3 \),
\[
\Delta V_{F_x} = \Delta V_{S_1} - \Delta V_{S_3}
\]
(2)

for \( F_y \) loading, in a similar way,
\[
\Delta V_{F_y} = \Delta V_{S_2} - \Delta V_{S_4}
\]
(3)

Here \( \Delta V \) means the change of voltage for strain gauge. The number of line for data collection is needed to cut down in order to minimize the integration circuit. Using equations (1), (2) and (3), unlike full bridge circuits used in load cell development, there are demerits which don’t compensate according to environment temperature change and have lower sensitivity than that of full bridge circuit.

3. Sensor fabrication and data acquisition

The fabrication processes is as follows [7]. The substrate used in this experiment is the DuPont Kapton HN polyimide film with thickness of 125 \( \mu \)m. In order to smooth the surface of the film, polyimide layer with thickness of 3 \( \mu \)m is spun on top surface of the film after dehydration baking. The polyimide layer is cured at 350 \(^\circ\)C for 2 hours.

Next, Ni-Cr alloy (Ni-Cr, 80:20) material is used as strain gauges due to its high resistivity and low coefficient of thermal resistance (TCR). 400 Å of Ni-Cr is defined on 100 Å of Cr adhesion layer using e-beam evaporator and lifted off. The first wiring metal layer of 2000 Å of Au is patterned on 200 Å of Cr using the same process as strain gauge’s step.

After the patterning of strain gauges and first wiring layer, the first passivation layer is spun on, patterned and cured using photo-definable polyimide (HD4000), its thickness is 3 \( \mu \)m. The HD4000 series polyimide is chosen due to its unique characteristic that is solvent developed and photo-definable. The second wiring layer, 3000 Å of Au is deposited on 300 Å of Cr adhesion layer using previous metal deposition method and then lifted off. In order to protect metal layer and define contact hole, second passivation layer is defined the same method and material as first passivation layer’s. The bump layer is patterned to measure normal and shear forces using multiple spins coating method. The height of tactile bump is 50 \( \mu \)m, and its size is 600 \( \mu \)m x 600 \( \mu \)m.

Finally, the Kapton polyimide film is etched to define membrane [6]. Thick photoresist layer is used as etching mask of the film in KOH solution. The used photoresist does not dissolve in KOH solution and is inexpensive compared with plated Cu. And then the wet etching of the film is carried out in KOH solution. After etching at 70 \(^\circ\)C for 15 minutes, the membrane of 50 \( \mu \)m thickness is defined. A photograph of the completed tactile sensor is shown in fig. 2.

3. Sensor fabrication and data acquisition

The fabrication processes is as follows [7]. The substrate used in this experiment is the DuPont Kapton HN polyimide film with thickness of 125 \( \mu \)m. In order to smooth the surface of the film, polyimide layer with thickness of 3 \( \mu \)m is spun on top surface of the film after dehydration baking. The polyimide layer is cured at 350 \(^\circ\)C for 2 hours.

Next, Ni-Cr alloy (Ni-Cr, 80:20) material is used as strain gauges due to its high resistivity and low coefficient of thermal resistance (TCR). 400 Å of Ni-Cr is defined on 100 Å of Cr adhesion layer using e-beam evaporator and lifted off. The first wiring metal layer of 2000 Å of Au is patterned on 200 Å of Cr using the same process as strain gauge’s step.

After the patterning of strain gauges and first wiring layer, the first passivation layer is spun on, patterned and cured using photo-definable polyimide (HD4000), its thickness is 3 \( \mu \)m. The HD4000 series polyimide is chosen due to its unique characteristic that is solvent developed and photo-definable. The second wiring layer, 3000 Å of Au is deposited on 300 Å of Cr adhesion layer using previous metal deposition method and then lifted off. In order to protect metal layer and define contact hole, second passivation layer is defined the same method and material as first passivation layer’s. The bump layer is patterned to measure normal and shear forces using multiple spins coating method. The height of tactile bump is 50 \( \mu \)m, and its size is 600 \( \mu \)m x 600 \( \mu \)m.

Finally, the Kapton polyimide film is etched to define membrane [6]. Thick photoresist layer is used as etching mask of the film in KOH solution. The used photoresist does not dissolve in KOH solution and is inexpensive compared with plated Cu. And then the wet etching of the film is carried out in KOH solution. After etching at 70 \(^\circ\)C for 15 minutes, the membrane of 50 \( \mu \)m thickness is defined. A photograph of the completed tactile sensor is shown in fig. 2.

3. Sensor fabrication and data acquisition

The fabrication processes is as follows [7]. The substrate used in this experiment is the DuPont Kapton HN polyimide film with thickness of 125 \( \mu \)m. In order to smooth the surface of the film, polyimide layer with thickness of 3 \( \mu \)m is spun on top surface of the film after dehydration baking. The polyimide layer is cured at 350 \(^\circ\)C for 2 hours.

Next, Ni-Cr alloy (Ni-Cr, 80:20) material is used as strain gauges due to its high resistivity and low coefficient of thermal resistance (TCR). 400 Å of Ni-Cr is defined on 100 Å of Cr adhesion layer using e-beam evaporator and lifted off. The first wiring metal layer of 2000 Å of Au is patterned on 200 Å of Cr using the same process as strain gauge’s step.

After the patterning of strain gauges and first wiring layer, the first passivation layer is spun on, patterned and cured using photo-definable polyimide (HD4000), its thickness is 3 \( \mu \)m. The HD4000 series polyimide is chosen due to its unique characteristic that is solvent developed and photo-definable. The second wiring layer, 3000 Å of Au is deposited on 300 Å of Cr adhesion layer using previous metal deposition method and then lifted off. In order to protect metal layer and define contact hole, second passivation layer is defined the same method and material as first passivation layer’s. The bump layer is patterned to measure normal and shear forces using multiple spins coating method. The height of tactile bump is 50 \( \mu \)m, and its size is 600 \( \mu \)m x 600 \( \mu \)m.

Finally, the Kapton polyimide film is etched to define membrane [6]. Thick photoresist layer is used as etching mask of the film in KOH solution. The used photoresist does not dissolve in KOH solution and is inexpensive compared with plated Cu. And then the wet etching of the film is carried out in KOH solution. After etching at 70 \(^\circ\)C for 15 minutes, the membrane of 50 \( \mu \)m thickness is defined. A photograph of the completed tactile sensor is shown in fig. 2.

3. Sensor fabrication and data acquisition

The fabrication processes is as follows [7]. The substrate used in this experiment is the DuPont Kapton HN polyimide film with thickness of 125 \( \mu \)m. In order to smooth the surface of the film, polyimide layer with thickness of 3 \( \mu \)m is spun on top surface of the film after dehydration baking. The polyimide layer is cured at 350 \(^\circ\)C for 2 hours.

Next, Ni-Cr alloy (Ni-Cr, 80:20) material is used as strain gauges due to its high resistivity and low coefficient of thermal resistance (TCR). 400 Å of Ni-Cr is defined on 100 Å of Cr adhesion layer using e-beam evaporator and lifted off. The first wiring metal layer of 2000 Å of Au is patterned on 200 Å of Cr using the same process as strain gauge’s step.

After the patterning of strain gauges and first wiring layer, the first passivation layer is spun on, patterned and cured using photo-definable polyimide (HD4000), its thickness is 3 \( \mu \)m. The HD4000 series polyimide is chosen due to its unique characteristic that is solvent developed and photo-definable. The second wiring layer, 3000 Å of Au is deposited on 300 Å of Cr adhesion layer using previous metal deposition method and then lifted off. In order to protect metal layer and define contact hole, second passivation layer is defined the same method and material as first passivation layer’s. The bump layer is patterned to measure normal and shear forces using multiple spins coating method. The height of tactile bump is 50 \( \mu \)m, and its size is 600 \( \mu \)m x 600 \( \mu \)m.
decreasing back to zero along the z-direction. Each test is repeated 5 times to confirm the reliability of the sensor. The responses of the tactile sensor according to applying normal load are plotted in Fig. 3. Under $F_z$ loading, the unit cell shows the excellent linearity and its hysteresis is negligible.

The responses of the tactile sensor according to applying normal load are plotted in Fig. 3. Under $F_z$ loading, the unit cell shows the excellent linearity and its hysteresis is negligible.

The shear force test is carried out when an applied force is varying the same rate as normal load along the x-direction as shown in Fig. 4. The outputs of the sensor according to applying shear load are represented in Fig. 4. During the force is applied along the $S_1$ direction as shown in Fig. 1(b), $S_1$ and $S_3$ are stressed and compressed, respectively. And then $S_2$ and $S_4$ are not significantly influenced. The sensor shows a high linearity under applied shear force.

5. Conclusions

The three-axial flexible tactile sensor has been designed and fabricated, which is comprised of micro force sensor (4 x 4), and its size being 13 mm x 18 mm. Each strain gauge has a square membrane, and its force capacity is 0.6 N in the three-axis direction. The advanced polyimide microfabrication technology was used to fabricate the sensing element of the tactile sensor. In order to conform the characterization of the sensor, the three-axial tactile sensor has been evaluated by applying normal and shear force between 0 and 0.6 N using the evaluation system with three-axial load cell. The average sensitivity $S_F$ of normal force and shear force is XXX and XXX with a linearity of XXX%, respectively. The test showed the tactile sensor that can measure normal and shear force simultaneously when touching objects. The experiments further enlarge the possibility that robots can have grasping ability using the demonstrated three-axial tactile sensor.

References