Microfabricated 3D Flexible Tactile Sensor with Table-shaped Structure for Intelligent Robot Fingers

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Abstract:

In this study, we propose new type of a low-cost flexible tactile sensor which can detect 3-axial force and suitable for intelligent robot fingers. In order to propose innovative device, problems of previous studies about materials and structures were analyzed and fabrication process is used by the polymer micromachining technique. The designed tactile sensor is comprised of several micro force-sensing units. An epoxy sensing plate with four legs was built on top of the flexible substrate with table-shaped. It can convert an applied force to a concentrated stress. The normal and shear forces can be detected by combining responses from metal strain gages embedded in a polymer substrate. Optimal positions of the strain gages were determined by the strain distribution obtained from finite element analysis. Although it has a simple structure, multi-functioned sensing algorithm without interference is possible.

1. INTRODUCTION

As the industrialization is progressed gradually to the high level, there are large ranges of needs on precise and complex measurements. There exist a variety of specially designated sensing device matched by each physical quantities. Although studies on human mimetic sensors –especially in the fields of vision and audition– have been performed actively, the situation is not the same for the tactile field. Until now, many kind of force sensors based on strain gages. However, some systems have been required high sensitivity and accuracy with small size, also not conventional load cells. Recently, Microelectromechanical systems (MEMS) technology shows the possibility of micro-scale force sensor. Since the micro force sensor, tactile sensors have been developed by using the micromachining technologies.

Recently, researches about touch sense are concentrated with needs for tactile sensor of intelligent robots fingers, because robot industry has been grown surprisingly up. To be used as a tactile sensor for an intelligent robot finger, the sensing device should have enough flexibility for the mounting of curved surfaces and the possibility to measure 3-axial force in order to convey concrete information to the robot for dexterous behavior by the detection of pressure and slip. In case of robot, the force or tactile sensor used as fingertip of robot hand can control and manipulate the grasping force of some objects through mechanical contact, when robot want to grasp arbitrary objects dexterously like humans. These tactile sensors can detect normal forces applied on the tactile pixels for gripping force control and generate tactile images for gripping positioning and object recognition. However, in addition to acquiring tactile images and normal forces, knowledge of tangential forces is also critical for force control, and thus, the force sensor is required to measure three components. Especially, the shear force component is very important from a viewpoint of slip detection between fingertip and object as well as estimation of static coefficient of friction. Sensing these full triaxial force profiles provides robots with a rich source of information about their physical environments.

Several tactile sensors have been developed through research activities, but they have some limitations. MEMS technology has the potential to be applied to integrated tiny sensing units, therefore many researchers have developed MEMS-based tactile sensors. Among them, sensors based on silicon have been tried first. Kane et al.(1) and Mei et al.(2). have fabricated a tactile sensor composed of some three-component force sensors with square membrane type using micromachining technology. Its fabrication is, however, not easy because of complexity of process and shape of the sensing element. Especially work to date has mainly focused on silicon-based sensors. Silicon micro-machined tactile devices offer excellent sensitivity and laboratory performance, but are limited by their fragility and lack of flexibility. The silicon material is mechanically brittle, and hence not capable of sustaining large deformation and sudden impact. Additionally, the silicon substrate is rigid, it is thus difficult to form continuous and conformal tactile sensor that can be used to cover contoured surfaces. For a wide variety of applications, sensors to be mounted on non-planar surfaces or even on flexible objects such as a human body. Another approach is to use flexible conductive or dielectric sheets, such as a FSR or PVDF films. These sensors can have a good flexibility but low sensitivity and spatial resolution. Therefore, according to the demand for small size and flexibility, micro-machining technology using polymer materials was proposed. A polymer-micromachining technology that enables the integration of MEMS devices on a flexible polyimide skin has been developed. Meanwhile, flexible-MEMS-based tactile sensors have been fabricated since new polymer materials have been developed. Engel et al.(3). have developed flexible tactile sensor skin using polymer micromachining. However, the sensor was mainly capable of measuring only normal force component. As various materials have been tried, results have appeared gradually. Although some MEMS tactile sensor based on a flexible polymer are reported recently, the 3-axial force detection and small size still remain as a challenge.

Therefore this paper described a design and fabrication of three-component micro force sensor with table-shaped sensing element.

2. SENSOR DESIGN

2.1 Structure Design and Specification

Sensory of robot should be similar to or superior to the human in order to replace human senses in dangerous or delicate circumstance. It is necessary for the tactile sensor used for fingertip of robot hand 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 forces oriented to the surface. Sensing and processing of these 3-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 order to determine the desirable performance specification of the tactile sensor like a human skin, the following survey lists for tactile sensor were referenced : spatial resolution 1-2 mm (this is the approximate minimum separation at which the human fingertip can distinguish two points applied to the skin as separate stimuli); threshold sensitivity about 0.05 – 0.1 N for one force-sensing element; stable and repeatable sensor response with no hysteresis[(4)]. From above performance lists, the design-specifications of tactile sensor based on three-component force sensors were as follows : spatial resolution is about 2 mm; curvature of the sensor is less than 8 mm; the normalized force capacity is 5 N.

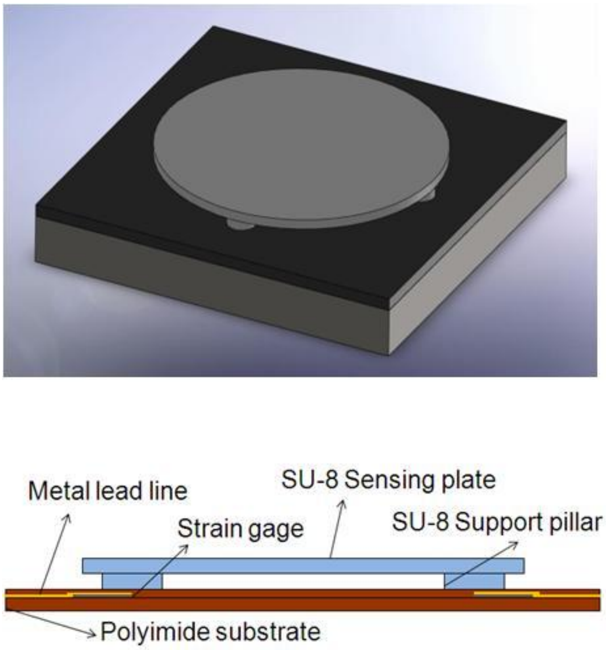

FIG 1. Schematic diagram of the sensing unit.

The designed tactile sensor consists of upper-plate as a sensing element of 60 µm thickness and 2.3 mm diameter and four force-transfer columns of 60 µm height and 0.44 mm diameter on the 4.2 mm x 2.9 mm square membrane of 125 µm thickness. Fig.1 shows the schematic diagram of designed three-component force sensor with four strain gages.

2.2 FEM Analysis and Location of Strain Gages

Most researchers have used finite element analysis to design a sensing element. In case of a sensing element with a thin membrane, generally, its deflection can be obtained theoretically by elasticity and thin plate theory. A commercial finite element program, ANSYS, was used in order to verify the design of sensing element.

We used the finite element model which consists of a force-transfer plate and four supporting pole on the membrane. Constrained bottom surface of membrane was boundary condition and it was applied to the tetrahedral mesh. Normal load, Fz, is applied uniformly to front surface of the upper-plate subjected to the force of 0.1 N. Fig. 2 shows the expected strain distribution result along inner edge of the column presented the symmetric distribution. Each shear load, Fx, Fy is applied uniformly to the side surface of the upper-plate subjected to the force of 0.1 N respectively. The strain distribution result placed edge of the column. It also coincides with the expected result.

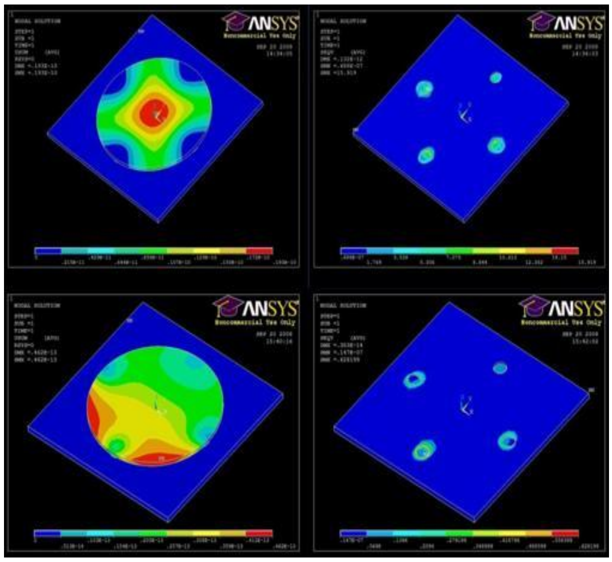

FIG 2. Strain distribution under normal(Z) and shear(Y) load

When the sensing element is subjected to three loadings, Fx, Fy and Fz simultaneously, the distribution of strain is very important in order to extract each signal from the force components without interference from the signals of strain gages. The optimal location of the strain gage was determined by the strain distribution obtained from finite element analysis. Using these strain distribution values, the shape of the strain gage and its size was determined in order to maximize the sensitivity of the sensor. From the analysis results, it is clear that the strain sensing elements in the tactile sensor must be placed at the periphery of the column.

3. SENSOR FABRICATION

The polymer material takes advantages that it has good thermal, electrical, mechanical, chemical stability. Therefore, polymer based 3-axial tactile sensors are eligible to be a solution for the fingertips of robot. The efficiency of several possible polymer materials was examined for the MEMS process. As the membrane material, polyimide film was used, having a Young's Modulus of 2.5 GPa, Poisson's Ratio of 0.34[(5)]. As column and upper-plate material, SU-8 was determined, having Young's Modulus of 4.4 GPa, Poisson's Ratio of 0.22[(5)].

The designed flexible tactile sensor realizes the surface micromachining technique based on photodefinable polymer material. The used polymer is SU-8 series epoxy which is a negative-tone, solvent developed. The sensing element is fabricated by polymer-micromachining technology. Strain gage and metal circuit line is deposited by photolithography on the Dupont Kapton HN film as a conventional polyimide film. And column and upper-plate using Microchem SU-8-3050 are also deposited by photolithography on the substrate. Fig.3 shows deposited metal strain gage and lead line on the polymer substrate.

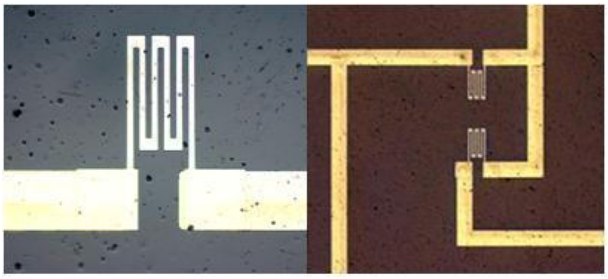

FIG 3. Deposited strain gage and lead line on the polymer substrate

Using standard photolithography, metal strain gages are deposited and patterned via lift-off process. The strain gages were made using 400 Å of Nickel-Chrome alloy(Ni-Cr, 80:20) due to its large resistivity in an effort to minimize the effect of contact and interconnect resistances on sensor performance. We have deposited the Ni-Cr material using sputter equipment. After polyimide membrane and resistance for strain gage, the composite film consisting of 4000 Å Au on 400 Å Cr was deposited and patterned via lift-off. In order to improve adhesion of the deposited metal films to the polyimide, the wafer was subjected to a 2 min oxygen planar plasma de-scum at 100 W after photolithography and prior to sputtering. Next, we made sacrificial layer using thick PR to foam three dimensional structure. Then, SU-8 epoxy as supporting pillar and sensing-plate was spun on and patterned to fully define the table-shaped structure. Finally the sacrificial layer was dissolved. Before performing the fabrication process, in advance, the investigation of the fabrication parameters of process material such as photolithography, metal-line deposition was conducted. The Ni-Cr alloy material for four strain gages was deposited and its shape is serpentine trace. As mentioned above, four strain gages were connected to one input line in order to decrease the number of data lines, and simplify the data acquisition system. The fabricated tactile sensor had an enough curvature diameter less than 8 mm which is the final goal of this work.

4. MEASUREMENT

The tactile sensor testing system is performed using a custom-built Interface Co. GPIB data acquisition circuit board PCI-3174 with A/D 16 Channel and 12 bit resolution. We get the resistance to the output gain through the sensor applying DC 3 V to the input line. Acquired data through the DAQ board is analyzed by offered program. In order to confirm the characterization of the sensor, sensing system was evaluated by applying normal and tangential force between 0 and 1.0 N. The tactile sensor presented the sensitivity of 33 Ohm/N in the normal loading and about 21 Ohm/N for tangential loading.

5. FUTURE PLAN AND EXPECTATIONS

We are currently continuing to upgrade performance of the sensor and evaluate feasibility. Next, we plan to investigate interference of force signals about enlarging 4 x 4 array of tactile sensing unit and perform standardization of the fabrication process from a viewpoint of yield improvement.

Polymer micromachining technology has been developed so far. Especially in field of materials, a variety of polymer was tried. However, it needs to develop fabrication technique which can control conditions well on reproducibility. It is expected that the polymer based sensor will be able to find its application for robotics as well as medical applications and welfare for the disabled. In addition, tactile mechanism is recognized as a next generation information input-output interface. The development of market for this field will be getting higher and higher in the near future because tactile sensing technology will be able to apply also tactile display part for virtual reality environments. Therefore, design and fabrication process technology through this work is look forward to taking a role as a core technology in a wide field. It is expected this approach makes it possible to develop functional tactile sensor array for use in dexterous robotic manipulation, medicine and industry field.

6. SUMMARY

In this study, we propose new type of a low-cost flexible tactile sensor which can detect 3-axial force and suitable for intelligent robot fingers. In order to propose innovative device, problems of previous studies about materials and structures were analyzed and fabrication process is used by the polymer micromachining technique. The designed tactile sensor is comprised of several micro force-sensing units. An epoxy sensing plate with four legs was built on top of the flexible substrate with table-shaped. It can convert an applied force to a concentrated stress. The normal and shear forces can be detected by combining responses from metal strain gages embedded in a polymer substrate. Optimal positions of the strain gages were determined by the strain distribution obtained from finite element analysis. Although it has a simple structure, multi-functioned sensing algorithm without interference is possible.

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