A Soft Three-Axis Load Cell Using Liquid-Filled Three-Dimensional Microchannels in a Highly Deformable Elastomer

Taekyoung Kim and Yong-Lae Park

Abstract—The advances in soft robotics have increased the need of soft sensors in various applications involved with physical interactions between humans and robots. In this letter, we propose a soft multiaxis force sensor made of multimaterial elastomer layers and embedded microfluidic channels that are sensitive to compression perpendicular to the channel length. The microchannels are geometrically divided into multiple segments for detecting forces in three axes. When a force is applied to the top surface of the sensor, the microchannels are compressed by multisegmented force plates made of rigid plastic. While the microchannels located on the sides in the structure detect shear forces, the microchannel at the bottom detects normal force. The three-dimensional configuration of the microchannel physically separates the side channels from the bottom channel and consequently enables mechanical decoupling of shear forces from normal force. The letter describes the design and fabrication of the proposed sensor and discusses the experimental results for sensor characterization.

Index Terms—Soft material robotics, force and tactile sensing, mechanism design.

I. INTRODUCTION

SOFT robotics technologies have been implemented to a wide range of robotics applications in recent years, such as medical robots [1], [2], wearable robots [3], [4] and mobile robots [5], [6]. They are particularly useful when the robots are involved with physical interactions with human users. For robots to be more interactive and friendly to humans, they need to be compliant and highly responsive when they are in contact with humans or external objects. To meet this requirement, different types of soft sensors have been developed. Examples include sensors made of elastomer materials mixed with conductive fillers, such as nanowires [7]–[9], nanotubes [10], carbon particles [11], [12], and graphene [13], [14], and embedded with liquid conductors, such as liquid metals [15], [16] conductive inks [17], [18], and ionic liquids [19]–[21]. Hydrogel soft sensors [22], [23] and optical soft sensors [24], [25] have also been proposed for increased bio-compatibility. Most of the above sensors rely on sensing mechanisms that detect single-axis deformation, such as a simple one-dimensional normal force or axial strain. However, in many robotics applications, force information with three-dimensional (3D) vector components is highly useful for control. Therefore, efforts have been made to develop soft sensors that can detect forces in 3D, such as multi-axis force sensors using flexible capacitors embedded in polymer structures [26], [27] and using microfluidic pressure sensitive channels [28], [29]. Although they can detect multi-axis forces, planar (i.e. shear) forces can be detected only when they are combined with a vertical (i.e. normal) force, which not only makes the sensitivity to the shear forces much smaller than that to the normal force but also makes it difficult to decouple the normal force from the shear force.

Therefore, we propose a new design of soft sensors (Fig. 1) that can detect multi-axis forces not only with increased spatial (or angular) resolution but also with an improved shear force sensitivity through a mechanism that directly detects planar components of the applied force in different angles [30]. Differently from previous sensors that have all the sensing elements located below the pressure point, our design has a 3D microchannel (Fig. 2) that is divided into sidewall and bottom channels, making possible to mechanically decouple shear and normal forces.

In the rest of the letter, we describe the design and fabrication of the proposed soft sensor in Sections II and III, respectively, presents the experimental setup and the characterization results in Sections IV and V, respectively, followed by considerations on materials in Section VI, and finally conclude and discuss future work in Section VII.

II. DESIGN

A. Sensing Mechanism

The basic sensing mechanism of the proposed sensor is detection of changes in electrical resistance of the embedded microchannel in a soft structure. The microchannels are filled with eutectic gallium-indium (EGaIn), a liquid-phase metal at room temperature [31]. By embedding multi-segmented force plates on top of the bottom channel and inside of the sidewall channels
B. Sensor Structure

The structure of the proposed sensor can be divided into two areas: the internal sensing area and the housing area. The internal sensing area is made of soft elastomer materials (Ecoflex 0030 and Ecoflex 0050, Smooth-On) including embedded EGaIn microchannels connected in series (Fig. 1(c)) and six 3D-printed force plates made of rigid plastic. The external housing area is made of a stiffer elastomer (Dragon Skin 30, Smooth-On). The stiffer housing plays a role as a backing for the microchannels and facilitates compression of the microchannels when a force is applied. The moduli of the materials used in our sensor are less than 100 kPa for the sensing area and less than 600 kPa for the housing area. The proposed sensor is flexible enough (Fig. 2(c)) to be used as skin for robots for physical interactions with humans.

C. Configuration of Microchannels

The microchannels are located both at the bottom and on the sides of the force plates in the sensing structure (Fig. 1(a)). The microchannel (Channel 4 in Fig. 1(c), 250 µm × 250 µm, square cross-section) located underneath the force plates detects normal force. Since it covers almost the entire area of the six force plates, a normal force applied anywhere on the force plates can be easily detected. The sidewall microchannels (Channels 1–3 and 5–7 in Fig. 1(c), 250 µm × 250 µm and 250 µm × 2500 µm) with 3D shapes (Fig. 1(a) and (c)) are divided into six segments and each segment was connected to its own signal wire for detecting a planar force in multi-directions. If a force is applied to the center of the sensor, one or more force plates will be displaced, compressing part of the bottom microchannel and one or two sidewall microchannels corresponding to the direction of the applied force. Therefore, it is possible to decouple the normal and the shear force components.

D. Force Plates

There are six force plates embedded in a circular shape at the center of the sensing structure. The slanted angle of each force plate and ridges on the top surface (Fig. 1(d)) facilitates the planar movement of the force plates. In addition, the protrusion on the side increases the sensitivity of the sidewall to shear forces. The actual prototype with embedded microchannels and force plates is shown in Fig. 1(e).

III. FABRICATION

The sensor was fabricated using a layered molding and casting method, as shown in Fig. 3 [15]. First, the internal sensing
KIM AND PARK: SOFT THREE-AXIS LOAD CELL USING LIQUID-FILLED THREE-DIMENSIONAL MICROCHANNELS

Fig. 3. Fabrication process: (a) Molding and casting of 3D microchannel layer, (b) sealing of open-top microchannels using spin-coating, (c) connecting and embedding signal wires, (d) embedding force plates, (e) injecting liquid metal (EGaIn) into microchannels, and (f) complete prototype.

structure with the microchannels and the force plates is made using a top and a bottom mold. While the top mold has a circular protrusion to make a space for the force plates, the bottom mold has a positive pattern (Fig. 3(a)). After being filled with liquid-state silicone (Ecoflex 0030), the bottom mold is covered by the top mold, and any excessive material is squeezed out of the mold. After curing in an oven at 60 °C for about 20 minutes, the molds are removed. The next step is to add a flat layer to the bottom of the sensing structure to seal the open microchannels. A thin, flat layer is made by spin-coating, partially cured, bonded to the bottom of the sensing structure (Fig. 3(b)), and then fully cured in the oven. After adding a signal wire to each microchannel, the housing is formed using stiffer silicone (Dragon Skin 30) in a new mold (Fig. 3(c)). The signal wire has a knot for preventing itself from being slipped out although the sensor structure experiences large deformation. A total of six force plates are placed in the empty space of the sensing structure, and soft liquid silicone (Ecoflex 0050) is poured on top to fully enclose the force plates (Fig. 3(d)). Before pouring of silicone, a low-friction film is inserted underneath the force plates to help their lateral movements, which increases the sensitivity to shear forces. Finally, EGaIn is injected into the microchannels using two syringes (Fig. 3(e)), and it completes the prototype (Fig. 3(f)).

IV. EXPERIMENTAL SETUP

Our prototype provides a total of seven signal outputs, one from the bottom channel and the other six from the sidewall channels for normal and shear force sensing, respectively. To generate multi-axis forces for experiments, a tabletop computer numerical control (CNC) milling machine (MT-3040B, RM) was modified by installing a hemispherical indenter (diameter: 10 mm) made of rigid plastic (Fig. 4). The CNC machine generates forces in three axes, which are applied to the soft sensor through the indenter. The resistance changes of the corresponding microchannels are then measured by a micro-controller (Arduino Due, SparkFun Electronics) through the custom amplifier circuit. While measuring the soft sensor outputs, the actual force is also measured by a commercial load cell (RFT60-HA01, ROBOTEUS) attached to the bottom of the soft sensor for comparison. The force data is acquired at 40 Hz in both sensors.

V. SENSOR CHARACTERIZATION

The soft sensor was experimentally characterized by applying forces in thirteen different directions, one normal direction and twelve planar directions combined with a normal component, as shown in Fig. 5. All the seven microchannels were connected in series, and constant current was applied. During the experiments, the CNC machine applied forces up to 13 N in the planar directions ($F_x$ and $F_y$) and 35 N in the vertical direction ($F_z$). The sensor data from both the soft sensor and the commercial load cell are shown in Fig. 5. When a pure z-axis force was applied, only Channel 4 showed a voltage output. When a combined force of $x$- or $y$-axis and z-axis was applied, the multiple channels corresponding to the force showed voltage outputs. When a force was applied between two force plates, the two channels corresponding to the force plates showed voltage outputs. Although the sensor had a limited number of the force plates, it was possible to interpolate the sensor signals and to detect forces in more directions than the number of the force plates. When a pure normal force was applied, the output from Channel 4 was high, since the bottom channel was compressed by the entire force plates. However, when a force with a shear component and the same level of a normal component was applied to a specific single force plate, the output from Channel 4

Fig. 4. Experimental setup for sensor characterization. CNC machine applies controlled force in three axes through hemispherical indenter, and sensor outputs are collected and compared with those of reference sensor (commercial three-axis load cell).
Fig. 5. Test result of multi-directional force sensing showing the directions and magnitudes of the applied forces and their corresponding sensor outputs.

Fig. 6. Test result to evaluate repeatability of the signals from each channel and the result of durability test during 1000 cycles, (a) the signals from channel 4 by the normal force repeated 10 times, (b)–(g) the signals from each sidewall channel by applying forces including both normal and shear force components repeatedly 5 times, (h) the result of durability test for normal force of −35 N during 1000 cycles, (i) the result of durability test for shear force sensing with the force of 7.5 N repeated during 1000 cycles (i) the schematic diagram of the channels and force plates.
Fig. 7. Test result to determine the effect of material combinations on the performance of the soft sensor. (a)–(c) the signals of each prototype for applying only normal forces (d)–(f) the signals for the shear forces applied in the direction corresponding to channel 2. The signal graphs show the hysteresis of each signal and the range of detectable forces depending on the soft sensors composed of different material combination.

was low because only one force plate compressed the underneath microchannel.

In addition to the force characterization, repeatability was tested, as shown in Fig. 6. For ten times of normal loading and unloading (Fig. 6(a)) and five times of shear loading and unloading (Fig. 6(b) to 6(g)), the soft sensor generated reliable outputs. Further tests for durability were also conducted. Our soft sensor showed physical robustness and signal reliability for over 1000 cycles of loading and unloading up to 35 N and 7.5 N in normal and shear directions, respectively (Fig. 6(h) and (i)).

VI. MATERIALS AND SENSOR PERFORMANCE

Since soft sensors made of polymer materials typically show nonlinearity with relatively large hysteresis, which was observed also in our sensor, we fabricated and tested three sensor prototypes with different combinations of silicone elastomers to examine the effect of materials.

The main purpose of this test is to find a combination of materials that can alleviate the hysteresis as well as improve the sensitivity in a low force range.

A. Material Selection

While the elastomer materials for the housing and the microchannel structures were fixed to Dragon Skin 10 and Ecoflex 0030, respectively, three different materials (Ecoflex 0030, Ecoflex 0050, and Dragon Skin 10) were tried for the top structure where the force is applied through the embedded force plates. Table I shows the material properties of the three silicone elastomers. According to the data sheet and the shore hardness scale provided in [32], Ecoflex 0030 is softer than Ecoflex 0050, and Ecoflex 0050 is softer than Dragon Skin 10.

<table>
<thead>
<tr>
<th>Material</th>
<th>Shore Hardness (00, A)</th>
<th>100 % Modulus (ASTM D412)</th>
<th>Elongation at Break</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoflex 0030</td>
<td>00–30</td>
<td>69 kPa</td>
<td>900%</td>
</tr>
<tr>
<td>Ecoflex 0050</td>
<td>00–50</td>
<td>83 kPa</td>
<td>980%</td>
</tr>
<tr>
<td>Dragon Skin 10</td>
<td>10 A</td>
<td>152 kPa</td>
<td>1000%</td>
</tr>
</tbody>
</table>

B. Experimental Result

The three sensor prototypes were tested by applying two different types of loads, normal force up to 28 N and shear force until the sensor output reached 2.5 V, one by one. The tests were done by making loading and unloading loops for each prototype.

The results show that the use of stiffer materials slightly decreased the pressure sensitivity but significantly improved the hysteresis for normal force (Fig. 7(a)–(c)). For shear force, although the stiffer top structure decreased the hysteresis level, it also significantly decreased the sensitivity (Fig. 7(d)–(f)). For example, while −5 N of shear force was required to achieve 2.5 V sensor output for Ecoflex 0030, −16 N of shear force was needed to produce the same level of sensor output for Dragon Skin 10.
TABLE II

<table>
<thead>
<tr>
<th>Measurement Range</th>
<th>Directly Detectable Force Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–35 N ($F_x$)</td>
<td>1 Normal</td>
</tr>
<tr>
<td>0–13 N ($F_y, F_z$)</td>
<td>12 Tangential</td>
</tr>
<tr>
<td>0–13 N ($F_x$)</td>
<td>1 Normal</td>
</tr>
<tr>
<td>0–1.8 N ($F_y, F_z$)</td>
<td>8 Tangential</td>
</tr>
<tr>
<td>0–5 N ($F_y$)</td>
<td>1 Normal</td>
</tr>
<tr>
<td>0–0 N ($F_x, F_z$)</td>
<td>6 Tangential</td>
</tr>
<tr>
<td>0–10 N ($F_x$)</td>
<td>1 Normal</td>
</tr>
<tr>
<td>0–40 N ($F_y, F_z$)</td>
<td>4 Tangential</td>
</tr>
</tbody>
</table>

Therefore, the multi-material structure of our sensor design requires investigations on materials for different applications.

VII. CONCLUSION

In this letter, we proposed a soft three-axis force sensor with enhanced spatial resolution and improved sensitivity for both normal and shear force sensing. The sensor was made of a combination of silicone elastomers (Ecoflex 0030, Ecoflex 0050, and Dragon Skin 10 from Smooth-On) and embedded microchannels filled with a liquid conductor. When a force is applied to the sensor, the microchannels deform and change the electrical resistance. Based on the direction of the force, only part of the microchannels change the resistance, which is used for detecting the direction of the force. In order to decouple normal and shear force components acting on the sensor, the microchannels were embedded in different locations relative to the force plates. While the bottom microchannel detects normal forces, the sidewall microchannel detects shear forces in multiple directions. In addition, the sidewall channel was divided into six segments with individual output signals for detecting forces in multi-axes. As a result, the proposed sensor was able to measure the applied force in 3D that contains both normal and shear components. Although the experiments tested only twelve directions for shear force sensing, the actual spatial resolution can be much higher if the sensor signals from two force plates are interpolated. Additional experiments were carried out to investigate the effect of the materials. The results showed that the hysteresis level and the sensitivity could be controlled by changing the combination of the elastomer materials of the sensor.

Although there have been soft sensors that can detect multi-axis force using either piezoresistive materials or liquid conductors [26], [27], [29], the main contribution of our work is to propose a new design of the sensor structure that can mechanically decouple shear force components from a normal force, which increases the sensitivity in shear directions. To achieve this, we developed a fabrication method for a three-dimensional microchannel structure embedded in the soft sensor structure. Furthermore, the idea of multi-segmented force plates not only decreased the thickness of the sensor but also increased the spatial resolution of shear force sensing. Table II compares our sensor with previously developed soft multi-axis sensor.

Although the current work demonstrated force sensing capability in three dimension with a soft structure, there is still room for improvement. Our immediate future work will include sensor characterization through machine learning that accurately reflects the full characteristics, since it is highly difficult to construct an accurate analytical model that can predict the nonlinear and hysteretic behaviors of soft structures. This will significantly increase the force estimation accuracy even with design limitations and uncertainties in material properties. Another future work will be the implementation and testing of our sensors to soft robots for high physical interactions with humans [33]–[35]. The mechanical compliance of the sensor not only will increase the friendliness of robots or machines but also can easily conform to complex curved surfaces making itself highly useful to be implemented in various types of existing devices, as discussed in [36].

ACKNOWLEDGMENT

The authors would like to thank Mr. Sohee Yoon and Mr. Kanghyun Ki for their technical support.

REFERENCES


