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Design of A Soft 3-Axis Load Cell for Human-Robot Interactions

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***Abstract*—This paper describes a soft three-axis tactile sensor composed of a soft-rigid multi-material structure embedded with microfluidic pressure sensitive channels. The sensor contains two types of microchannels filled with a liquid conductor for different sensing purposes: one for detecting normal forces and the other for detecting shear forces. While normal forces are measured by a single microchannel, shear forces are detected by a microchannel divided into six segments for an increased spatial resolution. The proposed sensor provides a total of seven output signals based on the direction of the applied force, making it possible to decouple force elements in x, y and z axes.**

***Keywords*—soft sensors, tactile sensors, force sensors, microchannel, liquid metal**

1. Introduction

The needs of soft sensors have been rapidly increasing with recent advances in human-robot interactions utilizing soft robotics technologies. For robots to be more interactive and friendly with human users, they need to be physically soft but, at the same time, should be sensitive to touch. Although various types of soft sensors have recently been developed using conductive polymers [1], [2] and liquid conductors embedded in a polymer matrix [3], [4], most of them are focused on sensing mechanisms for detecting linear deformations, such as normal strains or compressions. However, force data containing information on both directions and magnitudes have been one of the critical inputs for control in robotics. Although there have been some efforts on developing soft sensors for detecting forces in multi-directions, such as a three-axial force sensor using flexible capacitors embedded in a polymer structure [5] or a soft multi-axis force sensor using microfluidic pressure sensitive channels [6], their sensing mechanisms for shear forces are based on detection of normal forces on different pressure areas, which makes the sensitivity to shear forces much smaller than that to normal forces. In this paper, we propose a new type of soft sensors that can detect multi-axis forces not only with an increased spatial (or angular) resolution but also with improved shear force sensitivities through a mechanism that directly detects planar components of the applied force in different angles.

2. Design

The main sensing mechanism is detection of changes in electrical resistance of multiple microchannels embedded in a soft structure. The microchannels are filled with eutectic gallium-indium (eGaIn), a room-temperature liquid metal, and their electrical resistances are dependent on their dimensions. Since a pressure applied to a microchannel deforms the cross-sectional area and increases the resistance, the location of the channel in a polymer structure and the force application mechanism determines the directional sensitivity of the sensor. The sensor is divided into two parts: an internal sensing structure and an external housing structure. The sensing structure is made of highly soft materials (Ecoflex 30 and Ecoflex 50, Smooth-On), and the housing structure is made of a stiffer material (Dragon Skin 30, Smooth-On) than that of the sensing structure. The sensing structure contains all the eGaIn microchannels and force plates made of 3D-printed rigid plastic, as shown in Fig. 1-a. When a force is applied at the center of the sensor, one or more force plates move and press certain channels depending on the direction of the force. While the single serpentine microchannel (Channel 1) located underneath the force plates is for detecting normal force, the other channels embedded in the sidewall (Channel 2 through Channel 7) are for shear force sensing. The slanted angle of each force plate facilitates the plate's horizontal movement, which increases the sensitivity to shear force in addition to the stiffer housing structure that provides backing for the side channels. Figs. 1-b and 1-c show the design and the actual prototype of the sensor. Since the serpentine microchannel covers almost the entire area of the force plates, a normal force anywhere on the force plates can be easily detected.

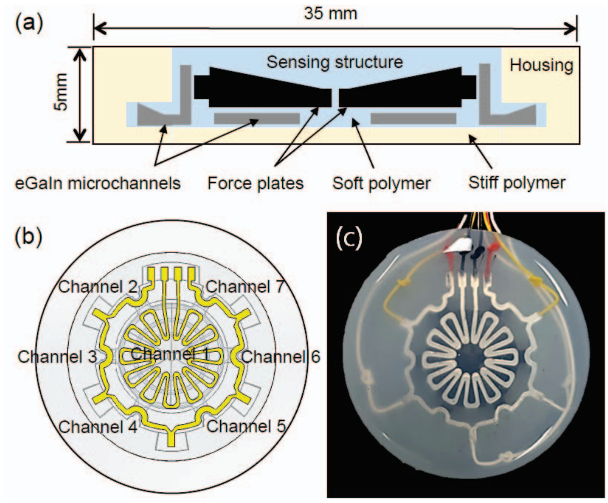

Fig. 1. Design of a soft multi-axis load cell (a and b) and a complete prototype (c) showing embedded microchannels in a soft polymer structure.

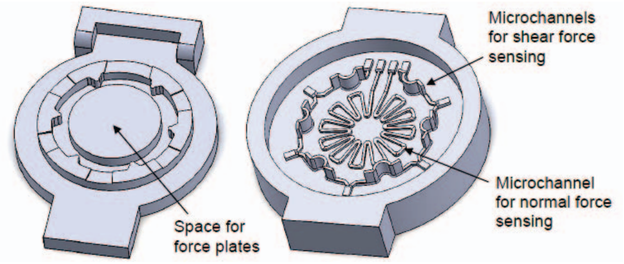

Fig. 2. Top (left) and bottom (right) molds for internal sensing structure.

3. Fabrication

The sensor was made using a layered molding and casting method [3]. Since the sensing structure contains not only the microchannels but also the force plates, it requires both top and bottom molds. The top mold has a circular protrusion that becomes a space for the force plates, and the bottom mold contains the positive patterns for microchannels, as shown in Fig. 2. Once the bottom mold is filled with liquid silicone (Ecoflex 30), it is closed and pressed by the top mold squeezing any excessive material out. After removing the molds, the open microchannels are closed by bonding another flat cured layer. Then, the force plates are inserted into the space from the top, and liquid silicone (Ecoflex 50) is poured again to hold the force plates. After filling the channels with eGaIn and connecting the signal wires by plugging into the channels, a different type of liquid silicone (Dragon Skin 30) for housing is poured externally and encloses the signal wires.

4. Results

The complete sensor prototype was tested by applying forces in eight different directions, one vertical force and seven planar forces that contain a similar level of the vertical force component. The applied forces were measured by a commercial multi-axis sensor. Fig. 3 shows the result of the experiments. All the six microchannels for shear force sensing (Channels 2-7) were connected in series, and the change of voltage drop on each microchannel was measured by applying a constant current. The voltage output for Channel 1 was measured individually. When a normal force was applied, only Channel 1 showed a positive output (Fig. 3-a). When a force is applied to a direction of a single force plate, the voltage outputs from Channel 1 and from the corresponding channel to the force plate (i.e. one of the six sidewall channels) were positive (Fig. 3-b through 3-g). If a force is applied in the middle of two force plates, the two corresponding sidewall channels to the force plates and Channel 1 yielded positive outputs (Fig. 3-h). Although the sensor has the limited number of force plates, it is possible to interpolate the sensor signals and detect forces in any directions.

5. Conclusion

This work demonstrated that a multi-axis force sensor can be made of soft materials, and a relatively high spatial resolution for detecting shear forces can be achieved. The sensor contains multiple microchannels filled with a liquid conductor that are sensitive to mechanical pressures. Based on the geometry and the configuration of the microchannels, the proposed sensor was able to decouple multi-axis forces. The preliminary test result showed the sensor's capability of detecting the directions and the magnitudes of the applied forces. An immediate area of future work will be a reliability test by analyzing the hysteresis and nonlinearity levels. Once the full characterization is complete, implementation of multiple sensors to robotic systems as a method of force and tactile feedback would be another area of future work.

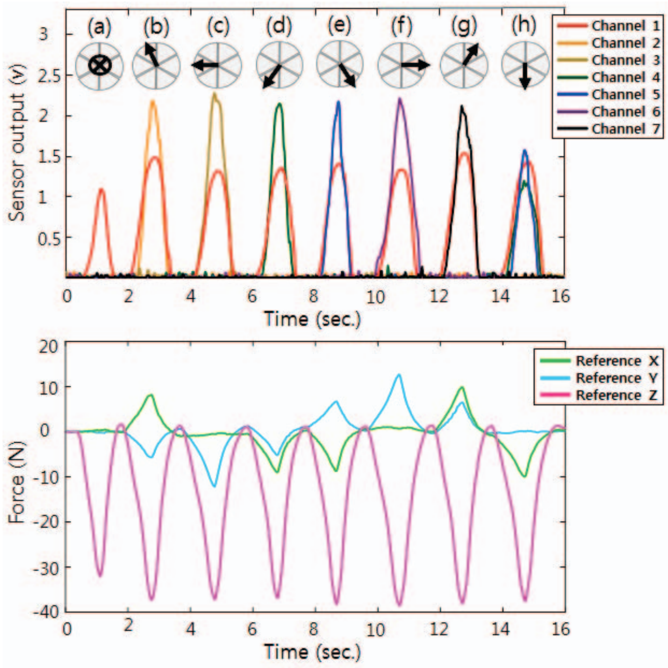

Fig. 3. Test result of multi-directional force sensing showing the directions and magnitudes of the applied forces and their corresponding sensor outputs.

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