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Stretchable liquid tactile sensor for robot-joints

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Abstract— **In this paper, we propose a stretchable tactile sensor composed of a pair of silicone rubber channels filled with electro conductive liquid. When a force was applied to this channel, its length and cross-sectional area deforms. By measuring the resistance change of the electro conductive liquid in the channel, its deformation can be measured. The proposed tactile sensor is composed of two parallel channel filled with electro conductive liquid, therefore, by comparing the resistance changes of each channel to the deformation, only the contacting force can be measured independently. Since a liquid is used for the sensing material, the proposed liquid tactile sensor can be easily attached to movable portions as the joints of robots.**

In the paper, we measured the sensing characteristics of the liquid tactile sensor to the stretch, bend, and contact force. Finally, the efficiency of the sensor was demonstrated by measuring the contact force from 0 to 3.0N by attaching the 20% stretched liquid tactile sensor to curved surfaces with 0.05mm^{-1} in curvature.

I. Introduction

RECENTLY, tactile sensors are required to control the robots with high accuracy and safety. For example, tactile information becomes important for dexterous manipulation of objects or to avoid collision between robot and human or other objects. To realize these methods, flexible tactile sensors to cover whole body of the robots not only its surface but also the joints are required.

Several types of flexible tactile sensors to cover the complex surfaces of robots, for example fingers and their tips, or surface of their body, were reported.

One approach is to embed micro devices for strain measurement into a flexible sheet as silicone rubber[1-4]. Kim(2006), reported on a 2mm square silicon chips with diagram composed of piezoresistor. By reducing the sensor size, it becomes able to bend. Although the devices used in these sensors were too rigid, it had difficulty to attach on a curved surface with small curvatures, for example tip of a finger.

Another approach is to use flexible materials as electro conductive rubber or thin metal layers. Someya realized a tactile sensor sheet using electro conductive rubber for pressure sensing[5-6]. This sensor can be attached to a curved surfaces as a finger tips. Hwang (2006) reported on a 3-axes force sensor using thin metal strain gauges formed on a flexible polymer sheet[7]. Lee (2007) reported a 3-axes force sensor with metal capacitors formed on an elastomer sheet[8]. Although the sensor using flexible materials are useful to cover the curved surfaces, it had difficulty to use in the movable portions. For example, electro conductive rubbers are easily influenced by the deformation caused with bending or stretch, and the thin metal layers are impossible to stretch. To consider the grasping or the collision avoidance, tactile sensors to cover the joints of robots without influenced by the movement become necessary.

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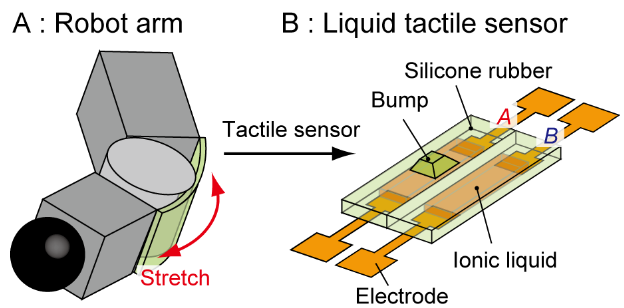

Fig. 1 Concept sketch of a liquid tactile sensor to detect contact force at movable portions.

In this paper, we reports on a stretchable tactile sensor using electro conductive liquid, as shown in Fig.1. This sensor detects the deformation of the channels by measuring the resistance changes of the electro conductive liquid. By using liquid as a sensing material, the sensor can be easily attached not only to the curves, but also to the movable portions as joints of the robot. To cancel the influence of stretching and bending caused and measure the contact forces at the joints, we arrayed two channels in parallel and compared their resistance changes.

II. Concepts

A. Concept of force detection

The concept sketch of the proposed liquid tactile sensor is shown in Fig.2. When the liquid tactile senor was attached to movable portions as robot-joints, major deformations caused to the sensor will be stretching, bending, and the deformations caused with the contact forces. To detect the contact force, it becomes necessary to cancel the influences of the stretching and bending. As shown in Fig.1B, the liquid

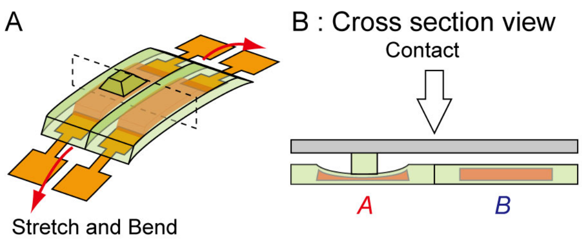

Fig. 2 Deformation images of the liquid tactile sensor to stretching, bending, and contact force. A is the whole image to the stretch and bend. B is the cross-sectional view of the deformation of channel to the contact.

TABLE I
CHARACTERISTICS OF 1-ETHYL-3METHYLIMIDAZOLIUM ETHYL SULFATE

Item	Physicality
Density [kg m^{-3}]	1237.6
Viscosity [Pa s]	0.09758
Electro conductivity [S m^{-1}]	0.398
Vapor pressure [Pa]	0

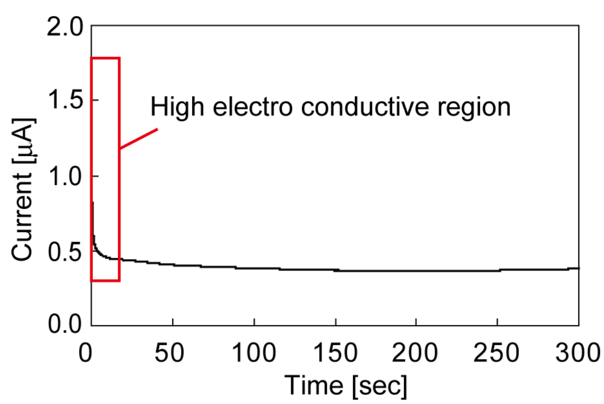

Fig. 3 Output current of the ionic liquid by applying 1.0V DC voltage.

tactile sensor is composed of two channels positioned close and parallel. If two channels were stretched or bended, the deformation and the resistance changes caused to them will become quite similar (Fig.2A). Therefore, the influences of stretching and bending can be canceled by calculating the resistance changes of two channels. Channel *A* and *B* is defined in Fig.1, channel *A* is the one with small bump on its surface and *B* is the one without the bump. We defined R_A as the resistance of the channel *A* and R_B as the resistance of channel *B*. From this definition, the contact force applied to the sensor can be calculated from R_A - R_B.

The bump structure formed on the surface of channel *A* concentrates the stress and increase the deformation of the channel *A* to the contact force (Fig.2B). Because of this characteristics, the contact force applied to the sensor surface can be measured independently from bending or stretching by

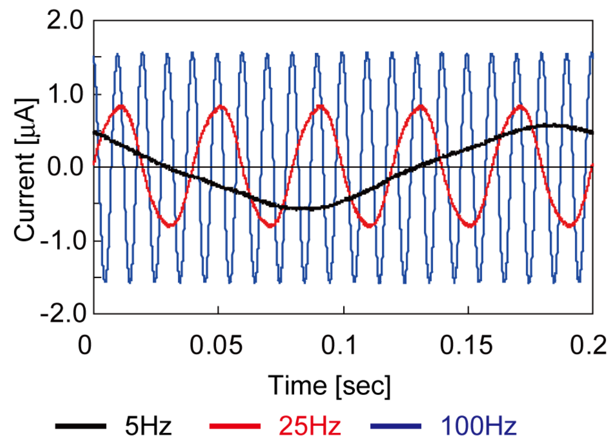

Fig. 4 Output current of the ionic liquid by applying AC voltage from 5Hz to 100Hz in frequency and 0.5V in amplitude.

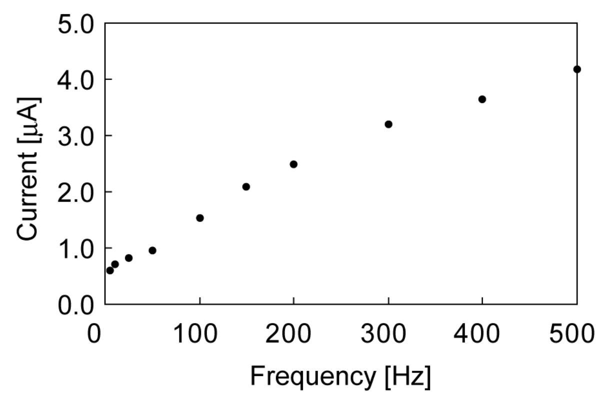

Fig. 5 Relationships between the frequency of applied AC voltage and the current of the ionic liquid.

calculating R_A - R_B.

B. *Resistance measurement of ionic liquid*

Ionic liquid is a liquid form salt composed of pairs of anion and cation (plus and minus ions) so that it has high electricity and mechanically, chemically stability. In this paper, we used ionic liquid, 1-ethyl-3methylimizodalium ethyl sulfate as the electro conductive liquid for tactile sensing. The major characteristics of 1-ethyl-3methylimizodalium ethyl sulfate are shown in Table 1.

When DC voltage was applied to the ionic liquid, its current changed as shown in Fig.3. In Fig.3 we filled a 2mm×20mm×0.3mm channel with 1-ethyl-3methylimizoda lium ethyl sulfate and measured its I-V characteristics by applying 1.0V DC voltage. As the result shows, the output current decreased from 1.7μA to 500nA after 3sec and kept decreasing till 5min. One assumption to this characteristic is that the density of ions inside the liquid changed by applying the DC voltage. Since the movement of the anions and cations inside the ionic liquid enables the current to pass through the

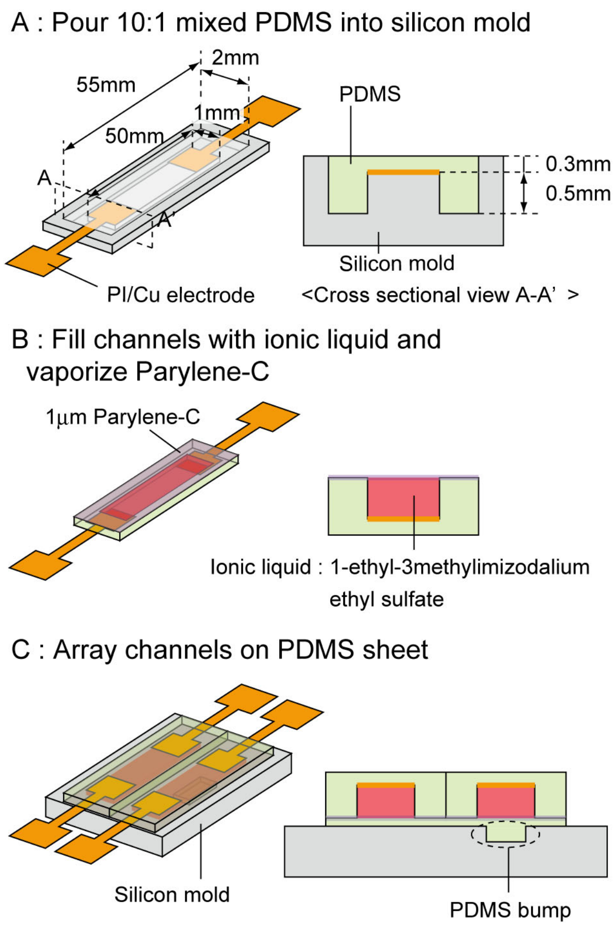

Fig. 6 Fabrication process of the liquid tactile sensor. Bird's eye view and the cross-sectional view of the device in each step.

liquid, its density will be important factor to decide the resistance of the ionic liquid.

According to Fig.3, the resistance of the ionic liquid become 3.0MΩ after 5min measurement and become difficult to detect small deformations of the channels. In this paper, we used AC voltage for measurement to resolve this problem. Fig.4 shows the output current when 0.5V amplitude, 5Hz to 100Hz Sine-wave voltage was applied to the ionic liquid (same as Fig.3A). By using the AC voltage as Sine-wave, the high electro conductive area of the ionic liquid (shown red in Fig.3B) can be repeated as an output. Fig.5 shows the relationships between the frequencies of applied Sine-waves and the maximum magnitude of peak of the output current. The graph shows that the amplitude of the output current increases with the frequency. This result shows the efficiency to use the high frequent AC voltage to measure the resistance of ionic liquid. In this paper, we used 25Hz Sine-wave as the input voltage to measure the resistance of liquid tactile sensor. This is because the limitation in the time resolution of measuring setups.

TABLE II
DIMENSIONS OF LIQUID TACTILE SENSOR

Dimensions	Value
Width [mm]	10
Length [mm]	55
Thickness [mm]	1.5
Liquid Volume [µl]	18
Initial Resistance [kΩ]	140

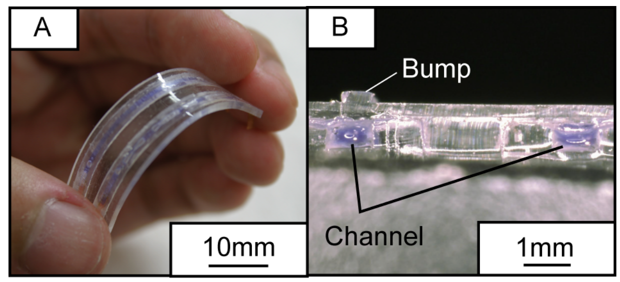

Fig. 7 Fabricated liquid tactile sensor, A is the whole view and B is the cross-sectional view at the bump.

III. FABRICATION PROCESS

A brief fabrication process of the liquid tactile senor is shown in Fig.6.

First, channels were fabricated by using silicon mold. The mold was fabricated by etching pure silicon wafer with RIE plasma dry etching. Silicone rubber, Polydimethylsiloxane (PDMS) was poured to the mold and cured with 70 degree Celsius for an hour. The PDMS and its hardening were mixed with 10:1 weight percent ratio (Young's modulus is 750kPa[1]). Before pouring the PDMS to the mold, electrodes fabricated with Polyimide/Cupper layers were attached to the mold's surface. Therefore the electrodes can be embedded inside the channels as shown in Fig.6A.

Secondly, the channels were taken off from the silicon mold and cleaned with O_2 plasma. By applying O_2 plasma to the surface of channel, it becomes hydrophilic. This helps to pour liquid to the channel. After cleaning, the channel was filled with 18µl ionic liquid (1-ethyl-3-methylimizodalium ethyl sulfate). The whole structure was covered with 1µm-thick Parylen-C polymer by vacuum deposition (Fig.6B) to keep the liquid volume. As shown in Table 1, a vapor pressure of 1-ethyl-3-methylimizodalium ethyl sulfate is high enough, its characteristics does not change under low pressure. This enables the vacuum deposition of Parylene-C to the ionic liquid[2].

Finally, two channels were arrayed on a PDMS sheet and connected by embedding in 10:1 mixture ratio PDMS (Fig.6C). This PDMS sheet was fabricated by using silicone mold as the same as Fig.6A. Since a 0.5mm×20mm×0.5mm bump was formed on the surface of this PDMS sheet.

The photographs of the fabricated device are shown in

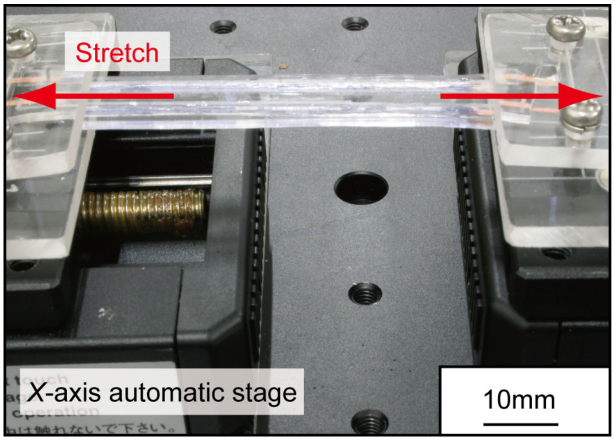

Fig. 8 Experimental setup for stretching the liquid tactile sensor with one axis automatic stage.

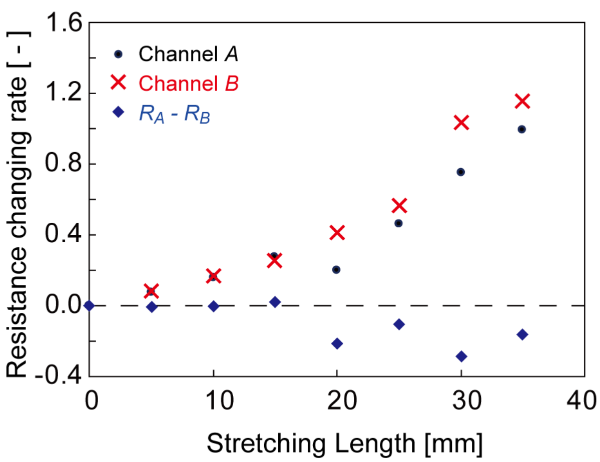

Fig. 9 Relationships between the magnitude of stretching length and the resistance changing rates of the two channels, and the compared results of their resistances $R_A - R_B$ . .

Fig.7. In these figures, the uncured PDMS colored in blue was filled in the channels to show their positions inside the sensor. Dimensions and the initial resistance of the fabricated sensor are shown in Table 2. As same as section II, the initial resistance of the sensor was measured with 25Hz, 1Vpps Sine-wave voltage.

IV. SENSING CHARACTERISTICS

By using the fabricated liquid tactile sensor, its sensing characteristics to the stretching, bending and contact force. The input voltage and its frequency was 0.5V and 25Hz as same as section II.

A. *Responses to Stretching*

The liquid tactile sensor was stretched with the setup shown in Fig.8. In this setup, the sensor was fixed on the top surface of one axis automatic stages with acrylic clamps. By using this setup, 35mm stretch was applied to the liquid tactile sensor in maximum. The relationship between the stretching

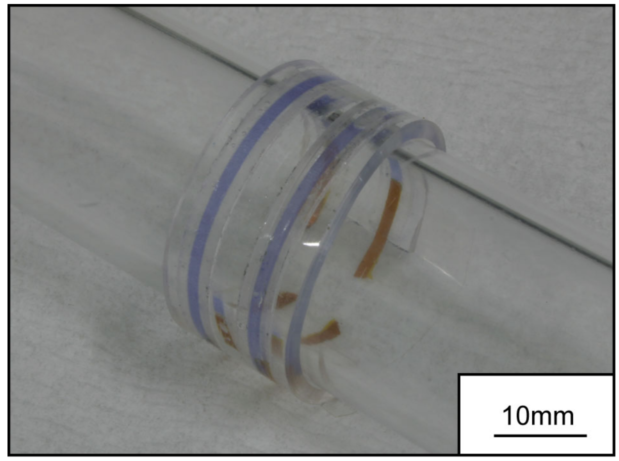

Fig. 10 Photograph of liquid tactile sensor attached on a rod with $0.1 mm^{-1}$ in curvature.

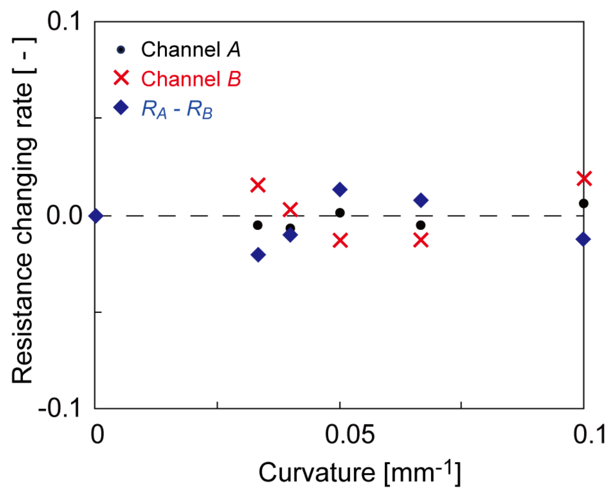

Fig. 11 Relationships between the curvature of attached surface and the resistance changing rates of the two channels, and the compared results of their resistances $R_A - R_B$.

length and the resistance changing rate of each channel is shown in Fig.9. In the graph, the resistance changes of two channels are shown with black and red dots and their compared result R_A - R_B is shown with blue dots. As it shows, the influence of the stretching to the initial resistance of the liquid tactile sensor can be reduced to 28% in minimum by calculating R_A - R_B. This result shows the efficiency to compare the two channels to cancel the influence of stretching.

In this experiment, the liquid tactile sensor broke after stretching for 35mm, which are 63% of its initial length. This was caused by the stretch rate of the PDMS. Although the stretch rate of PDMS (Sylgard184 Dow Coring Co.) is 120% in maximum, its limitation decreased by forming a thin channel. Therefore, the stretching range can be enlarged by changing the material and the design of the channel.

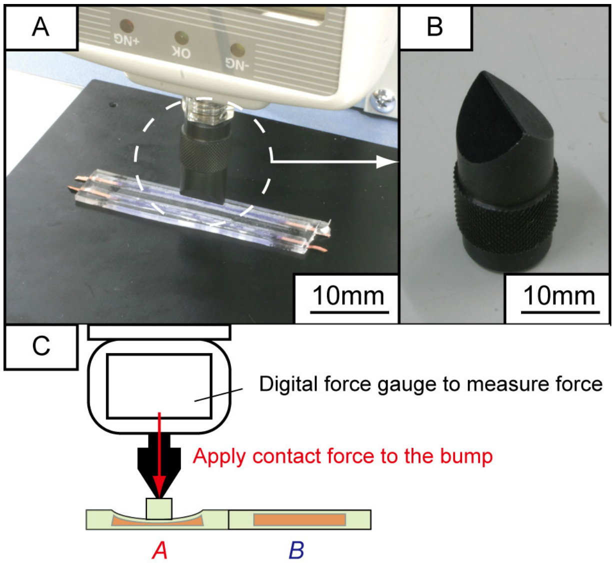

Fig. 12 Experimental setup to apply contact force to the sensor surface.

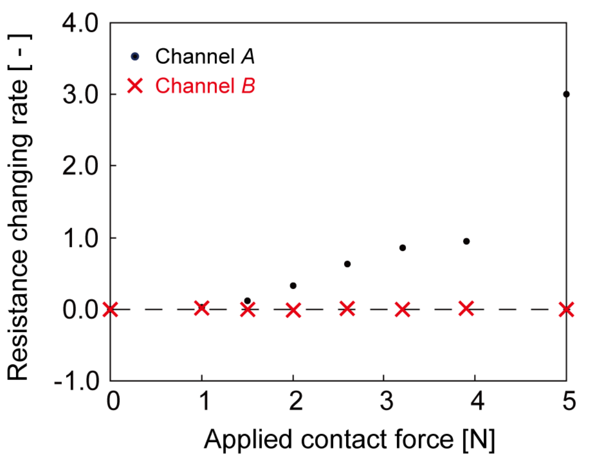

Fig. 13 Relationships between applied contact force and the resistance changing rates of channels.

B. Responses to Bending

The bending characteristic was measured by attaching the liquid tactile sensor on curved surfaces with 0 to 0.1mm^{-1} in curvature. Fig.10 shows the photograph of the liquid tactile sensor attached on a rod with 0.1mm^{-1} in curvature. The relationships between the curvatures of the attached surfaces and the resistance changing rates of the liquid tactile sensor are shown in Fig.11. The calculate result of is R_A - R_B shown in blue as same as Fig.9. Since the curvature 0.1mm^{-1} was as same as the size of the human thumb, an efficiency of the liquid tactile sensor to attach on finger was confirmed.

According to the result, each channel shows small change to the bending, the maximum change in resistance was 2% in every cases and confirmed that the bending show little influence to the sensor outputs. This was because of the design of the channel. The channels were positioned to the center of the structure to show small deformation in bending. From this characteristic and the result of Fig.9, the stretch can be measured independently from the resistance change of channel *B*.

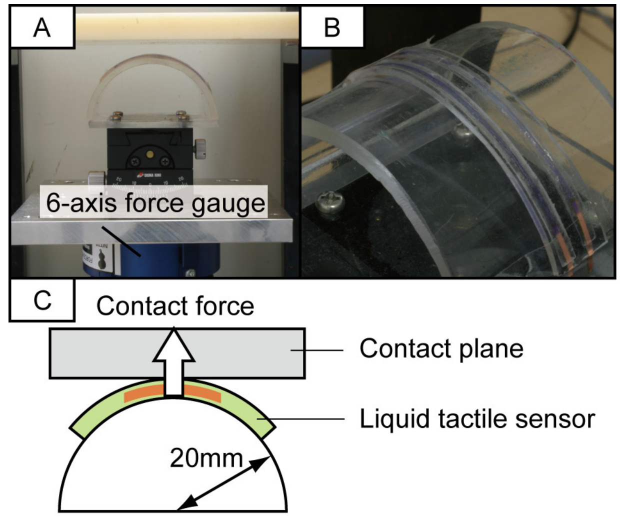

Fig. 14 Experimental setup to apply contact forces to liquid tactile sensor attached on curved surface with 0.05mm^{-1} in curvature.

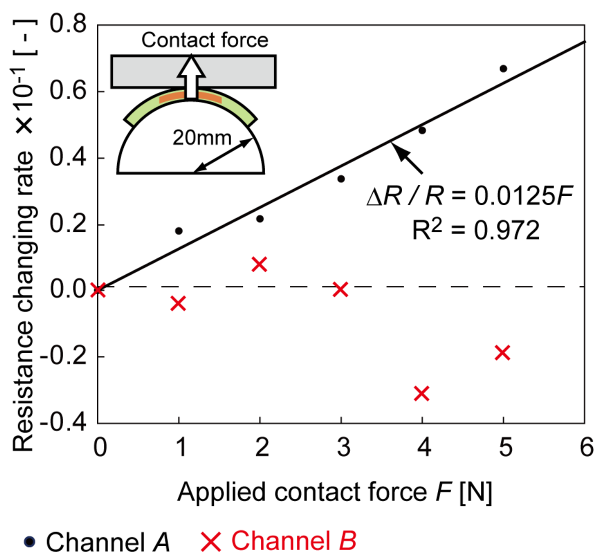

Fig. 15 Relationships between applied contact force and the resistance changing rates of two channels.

C. Responses to Contact Force

Since a bump formed on the surface of channel *A* will concentrates the contact force, the force only deforms the channel *A*. Therefore, we measured applied force to the bump on the channel *A* and confirmed its sensitivity to the applied force by using the setup shown in Fig.12. In this experiment, the liquid tactile sensor was attached to the flat plane and 0 to 5.0N forces were applied to its surface with a tip of flat blade with 1mm in width and 10mm in length (Fig.12B). The applied forces were measured by using digital force gauge. The *Z*-axis position of the blade was controlled with automatic stage. Fig.12 shows the relationships between the applied forces and the resistance changing rates of the channel *A* and *B*.

According to Fig.13, channel *B* showed quite small responses to the applied forces, less than 1% change of resistance were occurred by the applying forces. This result shows the independency of the responses of two channels to the applied forces. Therefore, it can be said that the resistance change caused by the pressure can be concentrated to the channel *A* by using a bump structure formed on its surface.

V. DETECTION OF CONTACT FORCES ON CURVED SURFACES

We confirmed the effectiveness of the proposed liquid tactile sensor by attaching the sensor onto a 20mm radius half rod and measured contacting force from 0 to 5.0N between the sensor and the flat plane shown in the photo. The photographs of setup are shown in Fig. 14. To attach the liquid tactile sensor onto the half-rod, we stretched the sensor for 20% from its initial length. The magnitudes of applied forces were measured with the 6-axis force gauge attached to the bottom of the half-rod. By using this setup, we applied 0 to 5.0N force to the sensor surface as shown in Fig.14B.

The relationships between the applied forces and the resistance change of the liquid tactile sensor are shown in Fig.15. As the result shows, the resistance changing rate of the channel *A* showed linear response (correlation factor R^2 = 0.972) and 10 times high sensitivity than the response of channel B in the range of 0 to 3.0N. From this result, it can be said that the liquid tactile sensor can measure the contact force efficiently by comparing the resistance changes of two channels from R_A - R_B.

If the applied force becomes larger than 3.0N, the channel *B* started to response to the applied forces. This is because the bump on the surface of channel *A* had been buried in side the channel and the channel *B* started to contact the flat plane when the contact force increased. Therefore, it becomes necessary to design the surface structure of the channel to control the sensing range of the liquid tactile sensor.

VI. CONCLUSION

We proposed and fabricated a stretchable tactile sensor using two channels filled with ionic liquid. To measure the resistance of ionic liquid, Sine-wave voltage with 25Hz frequency and 0.5V in amplitude was applied. By using AC voltage, the resistance of the device was reduced to 100kΩ. The fabricated liquid tactile sensor can measure the contact force from 0 to 5.0N. The influences of the stretching and bending were canceled by comparing the resistance changing rates of two channels. The resistance changes caused with 63% stretch in maximum and 0.1mm^{-1} curvature in minimum were canceled in this method.

By attaching the fabricated liquid tactile sensor on 20mm in radius half rod and measured contact forces to confirm its efficiency for force detection. To attach the sensor, 20% stretch to its initial length was applied. By comparing the resistance changes of two channels in the sensor, contact force from 0 to 3.0N was detected independently. From these results, we confirmed that the proposed liquid tactile sensor with two channels filled with electro conductive liquid is useful to detect the contact force at the movable portions as the robot-joints.

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