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Electrode for Force Sensor of Conductive Rubber

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ABSTRACT

Tactile sensors are believed to be a key element in order to realize robotic fingers to catch a fragile object without damage. Force sensitive conductive rubber is a low-cost material and then attractive for the application to tactile sensors. We have studied the effect of electrodes attached to the rubber sheets. We have tried four kinds of electrodes: vacuum deposited Al, adhesive Cu tape, Al thin film sheet and silver paste. It can be concluded that vacuum deposited Al has the highest potential from the practical point of view; it has the widest dynamic range and good precision at the same time.

Keywords: Conductive Rubber; Force Sensor; Robot Finger; Electrode; Vacuum Deposition

1. Introduction

When robotic fingers pick an object with a feedback control, a force sensor plays a key role to control the actuation of the fingers [1]. If the picked object is a soft one, the robot needs a sophisticated software and hardware system at the same time to hold it gently because it requires a precise control of the force loaded to it. The force sensor should be the most elaborate part for the robotic fingers in a bid to realize humanoid fingers. The tactile information is used as a control parameter in dexterous manipulation of humanoid fingers [2-4].

The solutions of tactile sensors have been fully reported. The types of the sensors are in a wide variety. A kind of them is based on a strain gauge or piezo-resistive device. The resistance variation brought about by the applied strain in this kind of device. The sensor arrays of this type have been reported nowadays [5-7]. The arrays of micro sensors demonstrated the ability in position sensing. In some cases, micro-machine technique was included to form this kind of sophisticated sensors. Some researchers have studied three dimension sensor arrays that can detect shear forces [8]. Other sensors of different types have been reported so far: piezo-resistor [9,10], capacitive [11,12], optical [13-15] and piezoelectric [16-19] ones. Furthermore unique ideas for the sensors have been reported such as conducting fluid [20], organic transistors [21,22], electron tunneling [23,24], ultrasonic [25, 26], magneto-resistive [27,28] and field emission [29] applications. In order to miniature the sensing system, silicon-based micro-electromechanical system (MEMS) has been widely applied [30,31] to piezo-resistive [32-35] or capacitive [36,37] type of the tactile sensors.

We pay attention to a conductive rubber sheet that varies electric resistance with a force applied to it. The conductive rubber consists of an elastomer enriched with conductive filler particles. The resistance of the rubber sheet reduces when external compressive force is applied. The material shows isotropic conduction. The advantage of the rubber sheet as a force sensor of robotic fingers is the low cost of the flexible material as well as the large area sensing ability [38]. In order to deal successfully with the short of reliability of the material, it requires an improvement in the formation of this sensor with a help of an intelligent adaptive control at the same time. Although elaborate ideas for the rubber sensor have been reported, basic and important properties such as electrodes for the rubber have been left behind. This article then treats the study on the dependence of the electrodes to the output characteristics as a sensor.

We investigated several kinds of electrodes that sandwiched the rubber sheet from the front and the back sides in four styles: Al thin film, Al deposited on the rubber sheet by vacuum deposition method, Cu thin film with conductive adhesive tapes and silver paste spread on the surface of the conducting rubber. The relationship of the output voltage to applied force have been studied and discussed from the point of view of a force sensor in robotic finger. The selection of the electrode directly affects the performance of the sensor devices. Nevertheless the close investigations have not been performed so far. This is partly due to the insufficient reliability of the rubber. It is expected to make a prototype low-cost tactile sensor for robot fingers with the help of adequate feedback control in the future.

2. Experimental Details

We used commercially available conductive rubber sheet (44 mm - 44 mm square and 15 µm in thickness) in our experiments. We prepared four kinds of metal contacts to the rubber sheets as follows. Silver paste spread (P-255 by Nisshin EM Co. Ltd.) on the both surfaces of the rubber sheet and then dried naturally (sample A). The rubber sheet was sandwiched with two pieces of Al thin film sheet (12 µm in thickness) and then the perimeter was fixed with a piece of adhesive tape (sample B). Adhesive conductive tape was affixed to the both surfaces of the rubber (sample C). The adhesive conducting tape of CU-35C (Sumitomo 3 M Limited) consisted of 35 µm thick copper foil and the electric conductive adhesive with metal particle dispersion. Sample D was formed by the deposition of Al by means of a vacuum evaporation method. In all cases, the metal electrodes covered about 90% of the surface on the both sides. The four kinds of electrodes were adopted from the point of view of simplicity in production. We show the photograph of sample D for example in **Figure 1**.

The prepared detecting circuit for the sensor is shown in **Figure 2**. The r denotes the resistance of the rubber sheet sensor that has several mega ohm without any force onto it and decreases down to the order of kilo ohm when the sensor is pressed by a finger. A resistor (3.9 kΩ) and a capacitor (4.7 µF) connected together in parallel was connected in series to the sensor, as shown in **Figure 2**. A DC voltage of 5 V was applied to V in **Figure 2**. The output voltage Vo was taken across the added circuit elements. The capacitor worked to reduce high frequency noise.

Figure 1. A photograph of sample D where Al was vacuum evaporated on the surface about 90% in area.

The Vo is transformed to a digital signal through an A/D converter, and then directly acquired by a computer, followed by a signal process with widely used software such as Excel and Matlab.

In order to apply the force uniformly in the surface area, the sensor was put between two solid plates. Force was applied with the help of a hand compressor. The applied force was monitored simultaneously using a load-cell put together with the rubber sheet sensor in the hand compressor. The range of the applied force was under 200 N in our experiments. When the maximum value of 200 N is divided by the area of 44 mm square and then multiplied by the 3 mm square area, we obtain the value of 0.93 N. This value well includes the typical force for the normal finger manipulation of 0.15 to 0.88 N (corresponding to 15 to 90 gf) [39,40].

3. Results and Discussion

We show here the four kinds of results in **Figures 3-6**, corresponding to samples A, B, C and D, respectively,

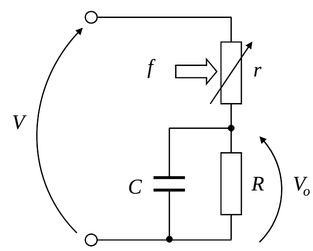

Figure 2. A detecting circuit for the rubber sensor r. Direct current voltage of 5 V was applied across the terminals (V in the figure), and the voltage of Vo was measured.

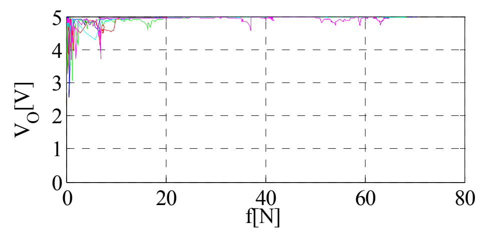

Figure 3. The dependence of Vo on the compressive force f in sample A (measured 5 times): silver paste was spread on to the both surfaces of a rubber sheet.

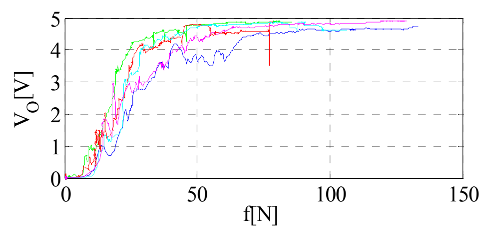

Figure 4. The dependence of Vo on the compressive force f in sample B (measured 5 times): Al sheet was just put on to the both surfaces of a rubber sheet and only the perimeter was fixed with an adhesive tape.

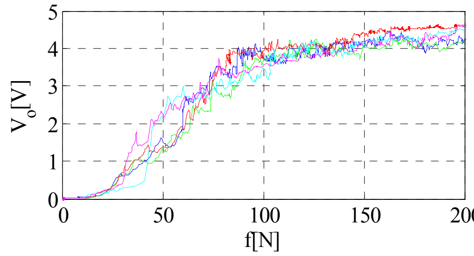

Figure 5. The dependence of Vo on the compressive force f in sample C (measured 5 times): a electrically conducting adhesive tape with copper foil was affixed to the both surfaces of a rubber sheet.

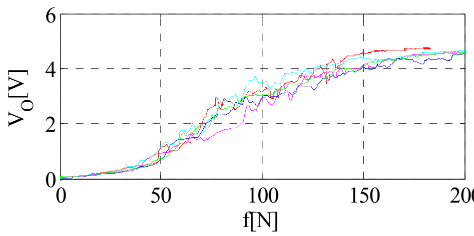

Figure 6. The dependence of Vo on the compressive force f in sample D (measured 5 times): Al was deposited on the both surfaces by means of a vacuum evaporation method.

that is the relationship between output voltage Vo and applied force f. We show Vo in the figures instead of the rubber resistance r, because we keep the feedback control in mind where the voltage Vo is of importance. Each figure includes several results to confirm the degree of reproducibility. Although the rubber sheets were well quality-controlled industrial products, the four kinds of results are interestingly quite different so that the difference is believed to be due to the effect of the electrode.

Figure 3 shows the fact that Vo was saturated no more than 10 N. It is quite peculiar characteristics compared with the other three results that Vo increased gradually along the applied force. Silver paste forms aggregate of silver particles in a solvent. It is surely easy to be buried in concavities over the rubber rough surface when the paste was smeared. It is an advantage for the silver particles soak into the rubber concavities to obtain close contact to each other from the view of contact resistance reduction. When a compressive force is applied, silver particles possibly penetrate in the rubber from the both surfaces, to result in a shunt between the two electrodes. This might cause the saturation of Vo in a quite small region in the applied force. It stems from the move of silver particles inside the rubber.

We see the result of sample B next. The sensitivity is the biggest in the three cases excluding sample A; Vo saturated above 50 N. The disadvantage of sample B is the worst reproducibility in the four. It possibly derived from the no fixation between the rubber and the electrodes. The compression force can cause the variation in the electrode contact state.

Figure 5 shows the Vo dependence on the applied force, when adhesive copper tape was adopted as electrodes (sample C). Saturation was observed above 80 N and so the dynamic range is twice as large as that of sample B. Though sensitivity is not large less than 25 N compared with that of sample B, it is noticeable that the reproducibility under 25 N is excellent. When the force was larger than 25 N, Vo increased steeply as the force increased to 80 N. In this region, however, the reproducibility was not good. We then define the two regions: stable region (under 25 N) and unstable region (above 25 N). The rubber sheet sensor is appropriate to be used in the stable region. In this sense, it can be said that samples A and B has no stable region. In the unstable region, the peeling off and sticking on between the rubber and adhesive tape irregularly occur and it seems to bear the dispersion of Vo, *i.e.* poor reproducibility.

Finally we see the case of sample D, where Al was deposited by evaporation, and discuss the characteristics here. The saturation of Vo was not observed in the range less than 200 N; the dynamic range is in other words, largest in the four types. The two divided region was also observed in this sample where the stable region is stretched up to 40 N. The stable region of sample D is largest in the four. It is surely because the Al electrodes and the rubber sheet is tightly bound to each other.

During the evaporation, Al gas reached the rubber surface even if the surface is quite rough. If the thickness of the deposited Al is smaller than the surface roughness, we can not obtain the continuous and crammed film and the electric conduction along the surface can not be well guaranteed. The thickness of the deposited Al films must be larger than the surface roughness of the rubber sheet. On the other hand, if the Al thickness is too large, it is presumed that the rubber becomes stiff consequently owing to the Al deposited layers. The optimum thickness of the Al electrodes is expected to be studied in the future.

The biggest problem of the conducting rubber sensor is generally the poor reproducibility derived from a inherent hysteresis property of the rubber. The problem can be possibly solved in part with the help of a histogram of frequency distribution of the sensor output and now under our study. At the same time, the electrodes strongly depend on the reproducibility as shown in this article. The improvement of the electrodes is actually of importance in order to develop the low-cost tactile sensor technology.

4. Conclusions

We have investigated four types of electrodes for a force-sensitive conducting rubber sensor. The electrical conducting rubber is expectedly applied to a tactile sensor with an advantage of low cost. The biggest problem of the material is to have hysteresis and poor reproducibility. The consideration of electrodes for the rubber sensor is inevitable but not yet well reported.

We found the output characteristics strongly depends on the form of electrodes, for example the dynamic range. The behavior of the output dependence should be divided into two regions: stable and unstable one. The stable region appears in a weaker force range and applicable to tactile sensors. In the unstable region, the rubber sensors show no good reproducibility. The range of the stable region is closely related to the contact state between the rubber surface and the electrode. As a result, the Al electrodes deposited by a vacuum evaporation method was found to have a largest stable region (0 to 40 N). This stems from the tightly binding between the electrodes and the rubber sheet.

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