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A Sputtering Deposition of Al Enhances the Output Reproducibility in a Conducting Rubber Force Sensor

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Abstract

Compressive force sensors or pressure sensors are indispensable to tactile sensors in humanoid robots. It is investigated that low-cost electro-conducting rubber sheets are applied to the force sensor, of which the biggest problem is its poor reproducibility. It was found that the aluminum deposition by a vacuum evaporation method shows excellent characteristics but suffers deterioration by a radiation heating effect. The aluminum electrode was deposited by a sputtering method, known to have an advantage of a low-temperature method, and the reproducibility of the output was improved.

Keywords

Conducting Rubber, Force Sensor, Electrode, Magnetron Sputtering, Reproducibility

1. Introduction

Tactile sensors are indispensable to humanoid robots, *i.e.* robot hands to pick up or to grasp an object. A humanoid robot is surely a kind of promising technology in the next stage of the robot field succeeded to present industrial robot technologies. Tactile sensors, which are undoubtedly in need to a sophisticated humanoid robot system, have been developed widely so far [1]-[4]. Some kinds of these sensors include strain gauge or piezo-resistive sensor arrays [5]-[7] for position sensing, as well as attractive sensors with capacitive or optical devices, organic transistors, ultrasonic or magneto-resistive devices, silicon-based microelectromechanical system (MEMS) and so on [8]-[37].

Among many kinds of compressive force sensors, electro-conducting rubber sheet is available formidably at low cost. Even if the low-cost sensor is quite attractive, this material has been left to be ignored. It is partly because the reproducibility of the relationship between force and output voltage is not good enough. This problem should be solved in the future. Under these circumstances, many challenges are faced to realize a better sensor with the conducting rubber sheet. The attention is focused onto electrodes on the both sides of the rubber sheet, described as follows.

Four kinds of Al electrodes were investigated: Al foil just put on the surfaces, silver paste spread on the surfaces, electro-conducting tapes and Al deposited by a vacuum evaporation method. It was found that the last one exhibited the widest dynamic range and the good reproducibility in the force range of usual use as robot fingers [38]. Afterwards it was clarified the radiation heating of the rubber sheet deteriorated the reproducibility. Hence, the low-temperature deposition of Al is required to improve it [39]. In this article, the Al electrodes formed by a sputtering method were introduced and the advantages of them are inspected.

2. Experimental Details

Commercially available conductive rubber sheets (30 mm square and 15 μm thick) were used. Three kinds of metal contacts were used to the rubber sheets as a top electrode. In sample A, an Al thin film sheet (12 μm thick) was put on the top surface without anything between them, and the perimeter of the Al sheets were fixed with adhesive tape. Sample B consisted of the same parts as Sample A but the Al thin film was fixed to the rubber with electro-conducting epoxy glue between them. In Sample C, Al film was deposited (780 nm in thickness) using a magnetron sputtering apparatus. The deposition was performed for 3 hours with the input power of 50 W.

Each sample was put on an Al plate without anything on the bottom of the rubber sheet. Another Al plate was put on the top electrode in order to apply the force uniformly over the surface area. Weights of 100, 300 or 500 g were put on the top Al plate to apply a constant force to the sensor. The three kinds of weight correspond to the forces of 0.11, 0.33 and 0.54 N per 1 cm^2, respectively. At least the last two values are in the region of normal finger manipulation, reportedly between 0.15 and 0.88 N [40] [41].

The measurement system of the output voltage response to time is described here. The prepared detecting circuit for the sensor is shown in **Figure 1**. The $r(t)$ denotes the

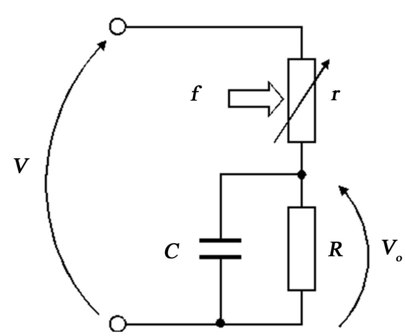


Figure 1. The detective circuit for the rubber sheet sensor (r).

resistance of the 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 (R = 15 kΩ) and a capacitor (C = 4.7 μF) connected together in parallel was connected in series to the sensor, as shown in Figure 1 [38]. The output voltage V_o was taken across the added circuit elements. The capacitor works to reduce high frequency noise. The V_o was measured every 5 ms untill 1 s. This 1-s scan was repeated 100 times at each measurement.

3. Results and Discussion

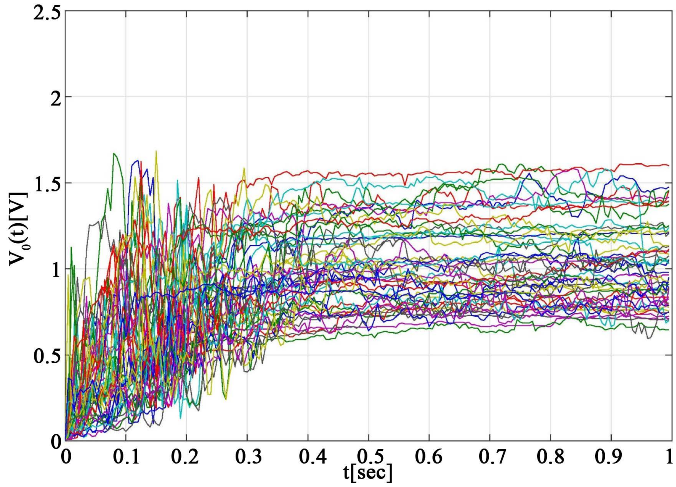
Figures 2(a)-(c) show the time response of V_o when the weight of 100 g was put on the Sample A, B and C, respectively. Figure 3 and Figure 4 are the similar experimental results for the weights of 300 and 500 g, respectively.

Generally speaking, the output voltage of V_o is settled down in nearly 0.4 s in all cases except for Figure 3(b). In Figure 3(b), V_o is not settled **down** enough until 0.6 s. It probably stems from the plasticity of electro-conducting epoxy glue. Samples A and C are free from the disadvantage because Al is directly contacted to the rubber surface.

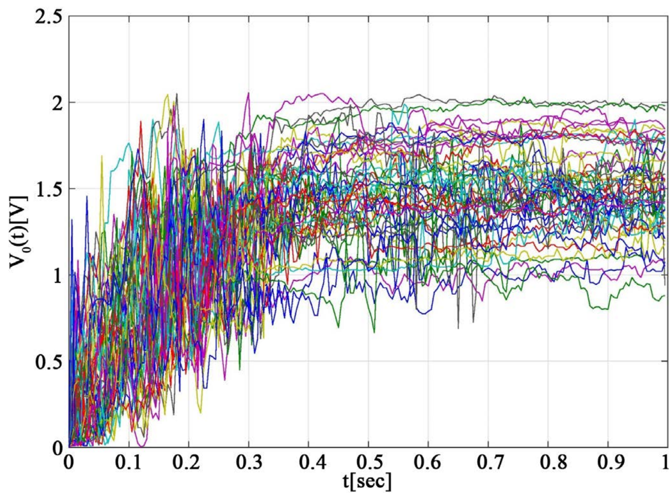
The final values of V_o is considered here. All the three samples have shown monotonic increase of V_o with respect to applied weight. The main concern is the relatively large errors of the final value. This is the case in all samples and noticeable in the case of 100 g. Fortunately in the region of usual manipulation, namely 300 and 500 g in our experiment, the relative error was lowered. In order to discuss the relative error, the dependence of the relative error is on the applied weight is shown in Figure 5. The figure apparently shows the relative error decreases with the applied weight in all samples. The tendency is convenient for the application to manipulation fingers because it meet the human sense.

The next issue is on the difference between the three samples. Figure 5 shows that Sample A gave the largest relative error in the three. It is natural because Al foil and rubber surface were not fixed to contact each other except for the peripheries. In both samples B and C, on the other hand, Al electrode is adhered closely to rubber surface microscopically. It was found that Sample C shows the smaller relative error than Sample B over 100 g. As a result, Sample C is most applicable for a practical use.

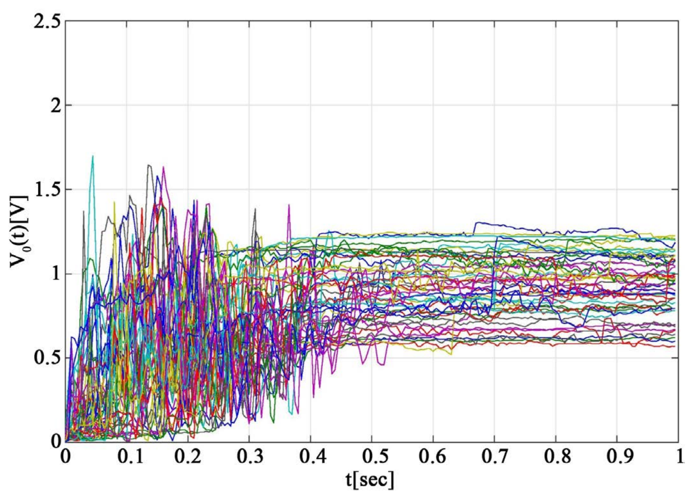
The error in the final value is discussed here. In all cases the error is characterized by the independence of time, or tends to take a constant value in one scan of measurement. The value is different at each scan. This fact derived from the inherent property of the conducting rubber that microscopic deformation of the molecules in the rubber is not the same at each scan. The discrepancy of the force can be detected if the difference of V_o is larger than the error. So Sample C is the most suitable in the three. One idea to suppress the error further, is taking an average of the final value of many scans. It might be realized in such a way that alternate actuation is applied for averaging. But it takes several seconds for obtaining the average. We expect to develop, in the future, a kind of methods to estimate the final value earlier than 0.4 s to reduce the time to obtain the average value.



(a)

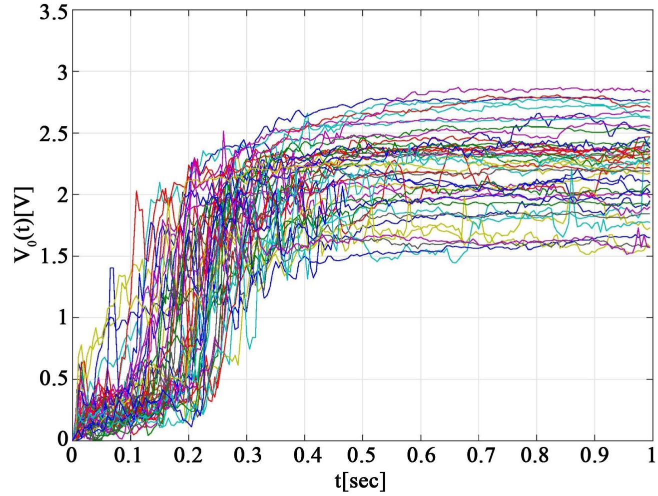


(b)

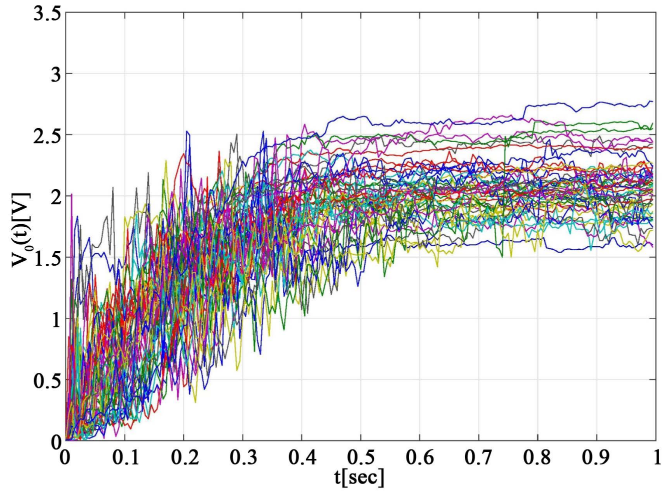


(c)

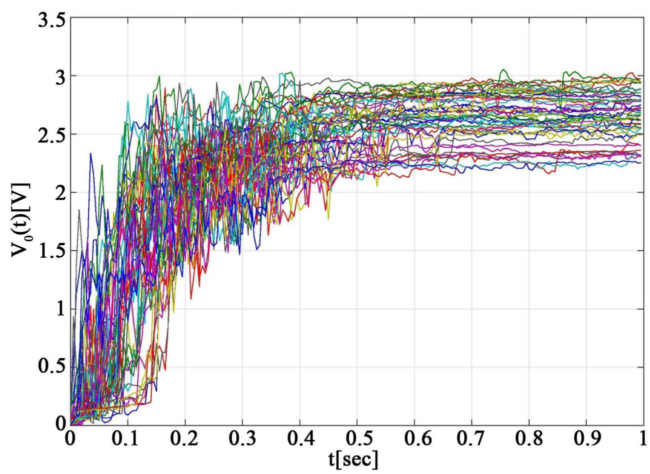
Figure 2. (a) The time response of the output voltage: 100 g, sample A; (b) The time response of the output voltage: 100 g, sample B; (c) The time response of the output voltage: 100 g, sample C.



(a)

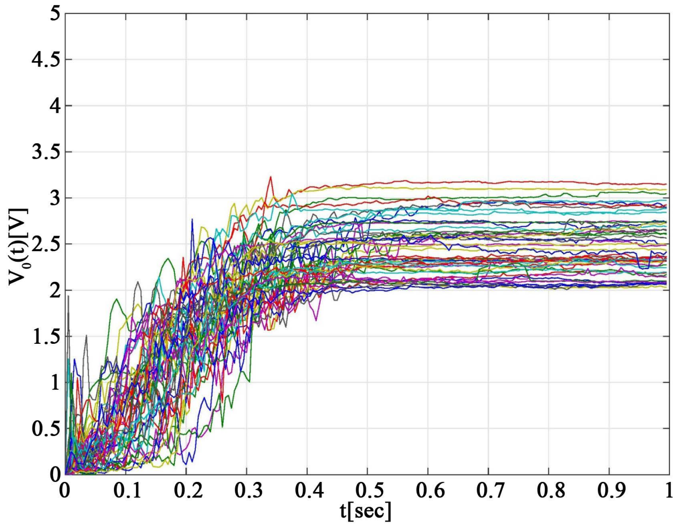


(b)

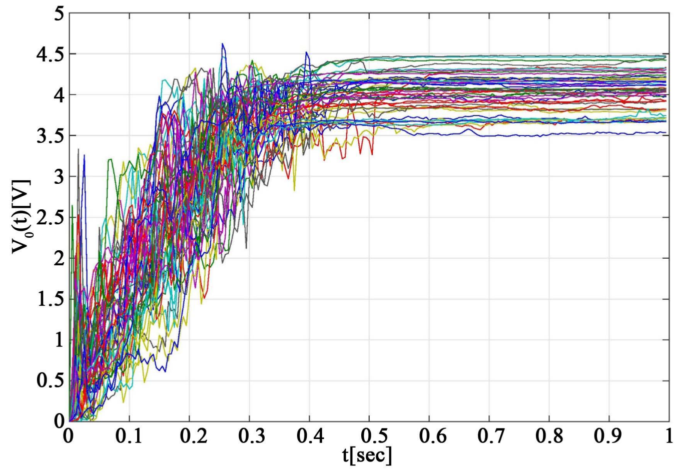


(c)

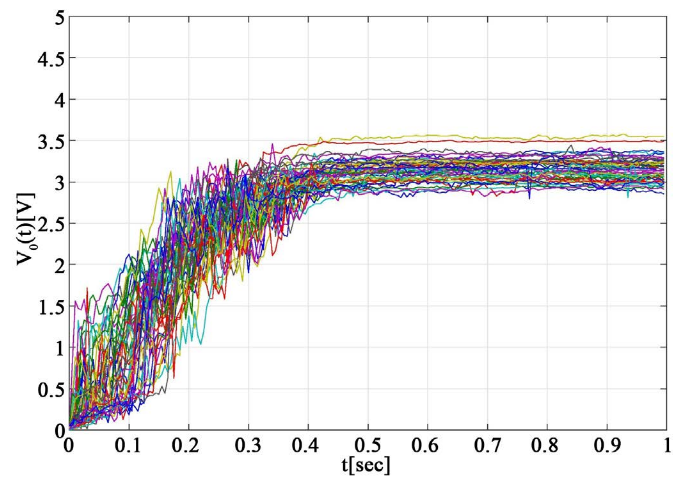
Figure 3. (a) The time response of the output voltage: 300 g, sample A; (b) The time response of the output voltage: 300 g, sample B; (c) The time response of the output voltage: 300g, sample C.



(a)



(b)



(c)

Figure 4. (a) The time response of the output voltage: 500 g, sample A; (b) The time response of the output voltage: 500 g, sample B; (c) The time response of the output voltage: 500 g, sample C.

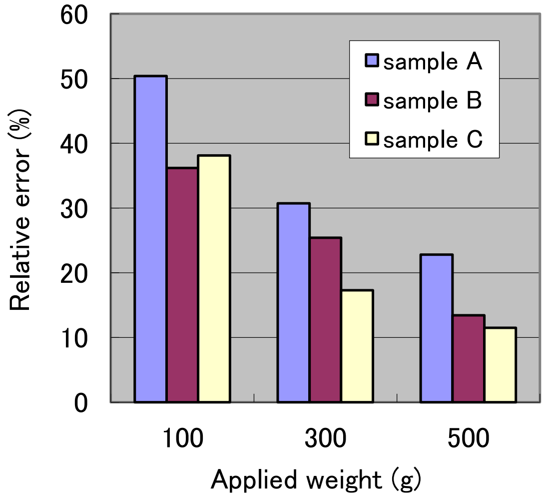


Figure 5. Relative errors reduce with the applied weight. It shows at the same time that Sample C comparatively gives small error in general.

We are now returned to consider the final value of V_o. The dependence of the average of 100-times experimental results of the final value of V_o is shown in **Figure 6** as a function of the applied weight. It is interesting to point that Samples A and C shows a convex property where Sample B shows a concave one. The convex property is more close to the logarithmic characteristics that is well known to fit to human's sense, namely the Weber-Fechner's theory, famous in a psychophysics field. In other words, the deviation from a linear relation works as a more human like behavior. Comparing the two samples A and C tells us that Sample C is more sensitive than Sample A. The higher sensitivity can provide the higher identification ability of the force from V_o. We conclude that Sample C is most applicable in the three from the point of view in **Figure 6**.

4. Conclusion

In this article, the characteristics of the output voltage from the force sensor of conducting rubber at the aim of application for low-cost sensors were studied. Three kinds of electrodes were investigated: Al foil just put on the rubber (Sample A), Al foil stuck to the rubber with electro-conducting epoxy glue between them (Sample B), and Al deposited by means of a sputtering method (Sample C). It was concluded that Sample C showed the most excellent characteristics in the three; the relative error is the smallest and the relationship between the output voltage and applied force shows a convex feature, so more likely to be logarithmic, which is close to the human sense as is well known as Weber-Fechner's theory. In addition, the high sensitivity in a small force region can contribute to the better estimation of the applied force. The conducting rubber gives inevitable error in final output voltage derived from its inherent property. It is surely a great challenge to reduce the error further with the help of the estimation of final value in a short time.

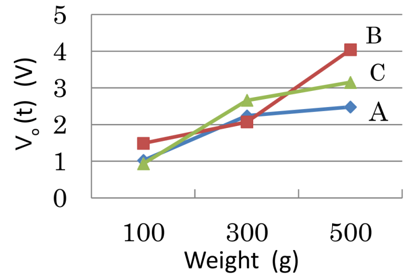


Figure 6. The dependence of the weight loaded on the rubber sheet sensor on the output voltage V_o. The signs A, B and C refer to Sample A, B and C, respectively.

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