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Development of Direct Printed Flexible Tactile Sensors

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〈Abstract〉

This paper proposes a structure of direct-printed flexible tactile-sensor. These flexible tactile sensors are based on pressure-sensing materials that allow pressure to be measured according to resistance change that in turn results from changes in material size because of compressive force. The sensing material consists of a mixture of multi walled carbon nanotubes (MWCNTs) and TangoPlus, which gives it flexibility and elasticity. The tactile sensors used in this study were designed in the form of array structures composed of many lines so that single pressure points can be measured. To evaluate the performance of the flexible tactile sensor, we used specially designed signal-processing electronics and tactile sensors to experimentally verify the sensors' linearity. To test object grasp, tactile sensors were attached to the surface of the fingers of grippers with three degrees of freedom to measure the pressure changes that occur during object grasp. The results of these experiments indicate that the flexible tactile sensor-based robotic gripper can grasp objects and hold them in a stable manner.

Keywords : Tactile Sensor, Pressure Sensor, Robot Gripper, Robot finger, Robotics grasping

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1. Introduction

Studies aiming to mimic human sensory organs have been popular over the last decade and, as a result, diverse sensors have been developed and are now used in several applications[1]. Although sensors that mimic human vision and auditory and olfactory senses have been developed and put into practical use, research into tactile sensors is still in its early stages. Two major reasons for this are that tactile sensors should have properties similar to those of human skin, and that complicated signal processing is required to detect pressure and other tactile sensations. Therefore, the development of tactile sensors requires not only research into the intrinsic characteristics and performance of sensors but also into signal-processing technologies to quantify and reprocess the output signals.

Tactile sensors are useful in a wide range of areas such as for artificial skin, medical robots, robotics for prosthetic arms, and intelligent robots[2]. In particular, tactile sensors are essential for robotic grasping systems[3-4]. Although existing systems can grasp a known object with constant force, many systems are not able to grasp objects that are not known a priori, which limits the flexibility of these automated systems[5]. However, by using feedback from tactile sensors that play the role of human skin, damages that occur when an object is grasped and the associated defect rates can be reduced, thereby leading to the stable robotic grasp of random objects [6].

Recently, many studies have appeared that discuss the development and application of various tactile sensors [7]. These include studies of capacitive pressure sensors, which were used to skilfully grasp objects, or optical three-axis tactile sensors that were incorporated in a robotic hand [8-9]. In other work, numerous strain gages were inserted into silicone rubber to form a tactile sensor for use with robot grippers. However, these approaches have certain drawbacks, such as the difficulty for sensors to cover large areas and insufficiently flexible sensors, which prevent them from being attached to a curved surface.

In this paper, we present a preliminary analysis of the performance of a flexible tactile sensor. The sensor uses lines of multi-walled carbon nanotubes (MWCNTs) sandwiched between two polymer layers. The sensor is fabricated by three-dimensional (3D) printing technology. Section 2 of this paper explains the sensor structure and the sensor fabrication procedure. Section 3 presents implementation of direct-printed flexible tactile sensors and presents performance evaluation for direct-printed flexible tactile sensor properties in section 4. Finally, the conclusions of this research are presented in Section 5.

2. Fabricating sensors by direct printing technology

2.1 Direct-printed flexible tactile sensors

Humans perform many tasks by using the tactile sensations felt through the skin. Through receptors in the skin, we measure physical quantities such as force, temperature, and texture. In particular, gathering information generated when we come into contact with external objects is one of the most important characteristics of human sensory organs. Tactile sensors are made by imitating human skin and, as such, should satisfy the following three conditions: First, the sensor elements that play the role of receptors should be arranged densely and with uniform spacing. Second, their elasticity and flexibility should be similar to those of human skin. Finally, the sensors should have the resilience necessary to restore their state after deforming by pressure [10].

To satisfy these conditions, tactile sensors based on diverse technologies are studied [11-12]. Representative technologies include sensors based on silicon microelectromechanical systems (MEMS), polymer MEMS-based sensors, nanostructured-material-based sensors, and, finally, tactile sensors based on pressure-sensing materials. Silicon-based tactile sensors offer the advantage of high spatial resolution of sensor elements but have the shortcoming of insufficient elasticity and flexibility due to their fragility. Polymer-based sensors can be fixed to curved surfaces, because they are flexible as they are made in the form of films. However, their disadvantages are system complexity and low sensitivity. Although nanostructured-material-based sensors are in the limelight at the moment because of their excellent performance, they cannot be implemented over large areas and require high performance for signal processing[13]. Pressure-sensing materials have excellent characteristics for tactile sensors because they have the resilience and flexibility similar to that of human skin and offer the advantage that they can be fixed to curved surfaces. Their disadvantage, however, is low sensitivity to minute pressure [14].

2.2 Mixture of pressure-sensing material

The pressure-sensing material is made of MWCNTs, which are conductive, and TangoPlus, a hardening material, by using a hybrid additive manufacturing technology [15]. The detailed manufacturing process of the materials responsible for pressure sensing is divided into the following five stages [16]:

(a) Add 0.5 wt% of MWCNTs and 1.5 wt% of sodium dodecyl sulfate (SDS) into dimethylformamide (DMF), which is an organic solvent, and disperse them by using an ultrasonic-magnetic agitator to

form a solution
(b) Disperse the prepared MWCNTs solution and TangoPlus by using the same ultrasonic–magnetic agitator
(c) Because residual solvent can affect sensor characteristics, maintain the solution at approximately 100 ℃ for 24 h while stirring with a magnetic agitator to remove the DMF
(d) After the residual solvent is removed, filter the solution (150μm pore size) to remove any agglomerations of MWCNTs that may have formed during synthesis
(e) By using a vacuum pump, remove all air bubbles that remain in the synthesized solution

MWCNTs offer high conductivity to the extent that they can be used as pressure-sensing materials for tactile sensor even if not mixed into solution with SDS by using DMF. However, upon applying external pressure, MWCNTs agglomerate together, and the agglomerates harden[17]. To prevent this, SDS is added, as shown in Figure 1, to maintain the entire mixed solution in a semisolid state. In addition, TangoPlus is added to give elasticity to the semisolid solution. In addition, an ultrasonic–magnetic agitator is used in a series of processes to minimize agglomeration of MWCNTs and to uniformly disperse them. Any remaining agglomerated MWCNTs are removed by filtering [18].

2.3 Fabrication of direct–printed flexible tactile sensor element

In this study, we fabricate direct-printed flexible tactile sensor elements by using a mixture of MWCNTs and TangoPlus as pressure-sensing material. Two MWCNT layers are sandwiched around an insulating layer, and the entire sensor element is surrounded by a material hardened using an ultraviolet (UV). The detailed hybrid additive

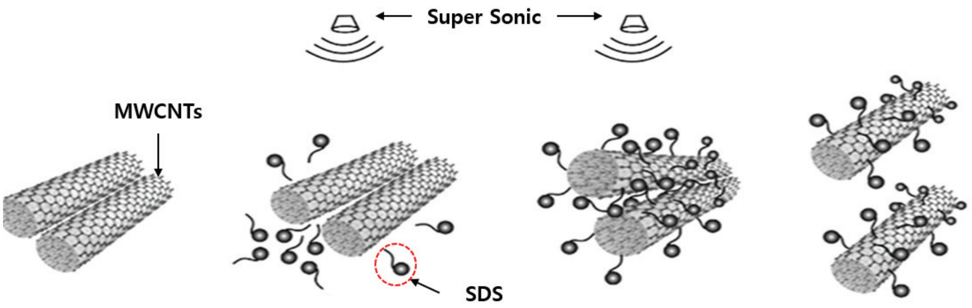

Fig. 1 Schematic illustration of fabrication process of MWCNT layer: 0.5 wt% MWCNTs + 1.5 wt% SDS solvent [19]

manufacturing process for the sensor element is divided into the following five stages:

(a) Pour the liquid-phase hardening material into a flat rectangular metal mold and irradiate it with a UV lamp to construct the lower sheet. Material thickness should be 1 mm
(b) Spray the pressure-sensing material (MWCNTs + TangoPlus mixture) in the desired form onto the hardened lower sheet
(c) Pour the liquid-phase insulating material into the mold and harden the material using the UV lamp. Material thickness should be 0.5 mm
(d) Spray the same pressure-sensing material as in step (b) to form the sensing area of the sensor element and harden the material using the UV lamp
(e) Pour in the same hardening material as used for the lower sheet to form a flat top sheet and irradiate it with the UV lamp to construct the lower part. Material thickness should be 1 mm [i.e., the same as for step (a)]

Figure 2 shows a schematic illustration of the architecture of the direct-printed flexible tactile sensor element and Figure 3 shows photographs of an actual tactile sensor element manufactured by the process given above. The sensor element consists of five layers. The TangoPlus, which constitutes the

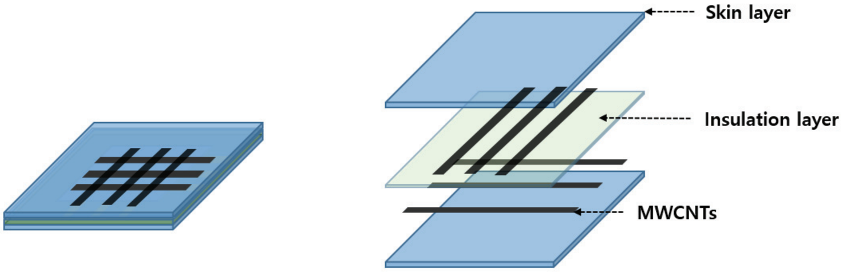

Fig. 2 Schematic illustration for architecture of direct-printed flexible tactile sensor element

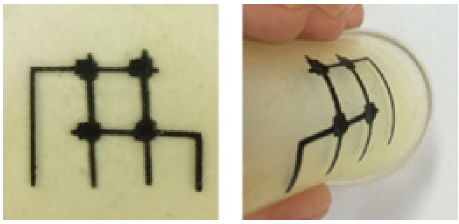

Fig. 3 Photograph of the direct-printed flexible tactile sensor element

surface of the sensor element, preserves the shape of the sensor element and gives the sensor element elasticity similar to that of human skin[20]. Although the sensor elements that correspond to the second and fourth layers are not physically connected to each other, they are designed to form a structure capable of generating output signals from the micro current generated by the insulating layer when pressure is applied [21].

Although the tactile sensor elements used in our previous studies have excellent signal sensitivity, they do not respond in real time to environmental changes because their resistance vary at the rate at which the pressure vary. In addition, their resistance decreases gradually after the first application of pressure. The flexible tactile sensor elements used in the present study, however, can measure pressure more accurately and stably and can measure pressure point by point instead of line by line [22-23].

3. Implementation of direct-printed flexible tactile sensors

The tactile sensor based on the pressure-sensing material requires filters to compensate for the impedance of the sensor element and remove noise generated by changes in pressure. In addition, such a sensor would require a signal-amplification circuit to amplify the small output signals.

Figure 4 shows the architecture of such a signal-processing module. The system is essentially divided into an analog- and a digital-signal-processing part. The analog-signal-processing part removes noise owing to the high impedance and the stabilizing signals. To remove the noise, we configure an integrating circuit based on resistors and condensers[24]. However, although this circuit removes noise, the system will still have high impedance. To reduce the impedance, we configure a voltage-follower circuit that will not affect the signal magnitude. Finally, to efficiently process the output signals coming from the sensor, a differential amplifier circuit is configured such that the circuit passes the output signals. To remain within the allowable range of the microcontroller (MCU), the magnification of the differential amplifier is set to approximately fivefold. The layout of the analog-signal processing circuit is illustrated in Figure 5.

Sensor signals that pass the analog-signal-processing circuit are digitized by the 12-bit analog-to-digital converter (ADC) input pin of the MCU and finally processed through digital filters. The ADC input pin of the signal-processing module consists of a total of 8 pins and measures signals at 40-ms intervals. In addition, an interface based on external communication is designed to conveniently monitor output-signal identification and control robot grippers.

Figure 6 shows the final signal- processing module. The MCU that controls main operations is designed by using dsPIC chips and it controls the amplification of sensor signals by tuning variable resistances. Communication between monitoring and sub- controller are ensured by two communication interfaces.

4. Performance evaluation for direct-printed flexible tactile sensor properties

To determine the characteristics of the sensor, an experimental device, as shown in Figure 7, was configured with an electrically driven test stand (i.e., a motorized test stand), a signal-processing module, and a monitoring system. First, pressure was applied to the tactile sensor through the electrically driven test stand and a force gage was installed on the test stand to measure the force at the given time. Since the force gage outputs nine measured values per second, the outputs of the controller were also set to be generated at the same intervals. The output voltage of the sensor passing through the integrating

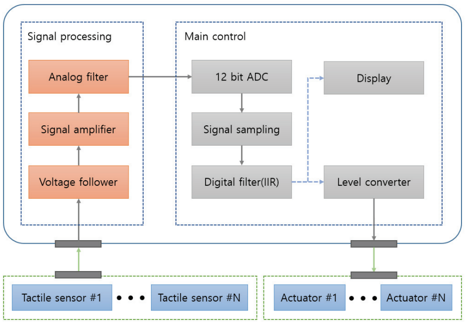

Fig. 4 Architecture of signal-processing module

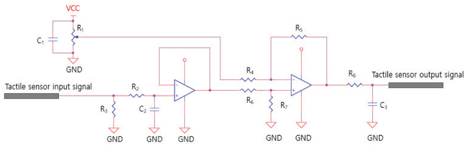

Fig. 5 Circuit of analog-signal-processing module

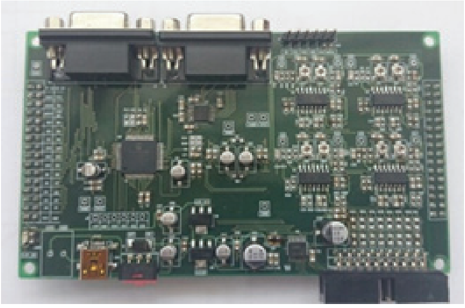

Fig. 6 Photograph of analog-signal-processing module for direct-printed flexible tactile sensor

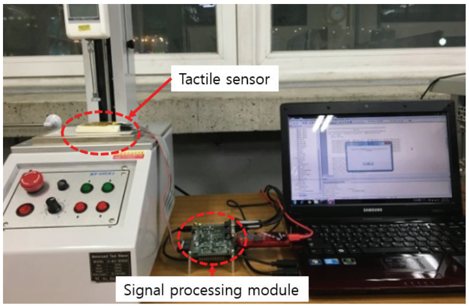

Fig. 7 Test-bed configuration for experiment.

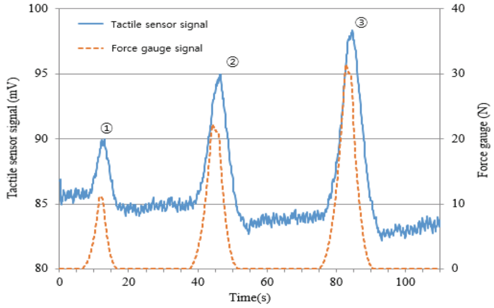

Fig. 8 Characterization of flexible tactile sensor for various pressures.

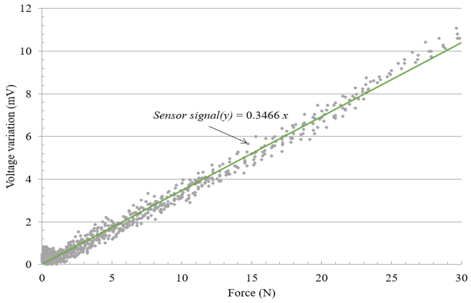

Fig. 9 Linearity error of direct-printed flexible tactile sensor.

circuit and the amplifying circuit of the signal-processing board was measured by the ADC pin of the main controller and the input signals were reprocessed by the digital filter in the main controller. The experimental device was configured such that processed data was transmitted to the monitoring equipment through RS232 communication.

To stably grasp objects of diverse shapes and weights, the performance of the grasping device should be verified by analysing the signals from the tactile sensor. In this section, we discuss how the tactile sensor's output signals were measured as a function of pressure and we analyse the linearity of the flexible tactile sensor. A pressure gage was installed on the test stand to apply diverse levels of pressure to the tactile sensor. Because the test stand can be turned on, off, or controlled only manually, the targeted pressure can be obtained detecting.

Therefore, to experimentally determine the sensor characteristics, pressures close to 10, 20, and 30 N were applied to the tactile sensor instead of accurate pressures of 10, 20, and 30 N, respectively. Figure 8 shows the output signals from the tactile sensor as a function. In the figure, the dotted lines indicate the magnitude of the applied pressures (N) and the solid lines indicate the output voltages of the sensors (mV) as a function of pressure. Forces 10, 20, and 30 N were successively applied to create pressure on the sensor. As seen in Figure 8, when pressure was initially applied, we verify that the output voltage was increased. But, when pressure was eliminated, the output voltages of point 1, 2, and 3 are different. This is because the characteristics of the sensor element change as a function of elasticity and resilience of the sensor element. The magnitude of the output signal decreased gradually when the initial pressure ceased. Considering these characteristics, the experiment involving grasping objects was conducted after applying the initial pressure (see Section 4).

A second experiment was conducted to

determine if the flexible tactile sensor is linear. We evaluated the output signals by using the change in voltage in the section where pressure rises as shown in Figure 9. The linearity error was calculated by using linear regression method as follows:

$$
\begin{aligned}
\%e_{L_{\max}} &= \frac{|e_L|_{\max}}{r_0} \times 100 \\
r_0 &= y_{\max} - y_{\min} \qquad (1) \\
e_L(x) &= y(x) - y_L(x)
\end{aligned}
$$

Where $\%e_{L_{\max}}$ is the linearity error and r_0 is the full scale operating range. $e_L(x)$ is the difference between sensor output voltage, $y(x)$ and linear regression, $y_L(x)$.

In the figure, as $y_{\min}$ was 0 mV and $y_{\max}$ was 11 mV approximately, we know that r_0 was 11 mV. When the force magnitude is 15.9 N, we verify that the largest difference is 0.4466 mV. Based on equation, we verify that the linearity error is 4.06%.

5. Summary and conclusions

We developed a robotic grasping system that can stably grasp objects by using direct-printed flexible tactile sensors based on a pressure-sensing material. Experiments with the system demonstrate the performance of the sensors. In addition, to process the sensor signals, we designed and fabricated signal processing boards consisting of analog signal filters and amplifying circuits, which was used to analyse signals generated by pressure on the sensors. With this apparatus, the linearity of the sensors was characterized experimentally.

Although tactile sensors may find applications in diverse field, they have been most recently in the limelight for robotic grasping systems. In the present study, we determined that tactile sensors based on pressure-sensing material can be used to create stable grasping systems by industrial robots and other diverse machines that use grippers. In future work, sensor signal processing allowing the sensing of pressure over large areas and the measurement of horizontal forces, temperature, and object texture should be developed. In addition, diverse studies are still required to develop robotic-gripper control algorithms that exploit sensor feedback.

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References

[1] Kim, J.-M., Kim, J.-H., Cha, J.-Y., Kim, S.-Y., and Kang, I.-P., 2012, “A biomimetic artificial neuron matrix system based on carbon nanotubes for tactile sensing of e-skin,” Journal of Institute of Control, Robotics and Systems, Vol. 18, No. 3, pp. 188-192.

[2] Lumelsky, V., Shur, M. S., and Wagner, S., 2000, “Sensitive skin,” Selected topics in electronics and systems, Vol. 18.

[3] Kawamura, T., Inaguma, N., Nejigane, K., Tani, K., and Yamada, H., 2013, “Measurement of slip, force and deformation using hybrid tactile sensor system for robot hand gripping an object,” International Journal of Advanced Robotic Systems, Vol. 10.

[4] Romano, J. M., Hsiao, K., Niemeyer, G., Chitta, S., and Kuchenbecker, K. J., 2011, “Human-inspired robotic grasp control with tactile sensing,” Robotics, IEEE Transactions on, Vol. 27, No. 6, pp. 1067-1079.

[5] Shimojo, M., Namiki, A., Ishikawa, M., Makino, R., and Mabuchi, K., 2004, “A tactile sensor sheet using pressure conductive rubber with electrical-wires stitched method,” Sensors Journal, IEEE, Vol. 4, No. 5, pp. 589-596.

[6] Iizuka, K., Sasaki, T., Yamano, M., and Kubota, T., 2014, “Development of Grousers with a Tactile Sensor for Wheels of Lunar Exploration Rovers to Measure Sinkage,” International Journal of Advanced Robotic Systems, Vol. 11.

[7] Dahiya, R. S. and Valle, M., Tactile sensing for robotic applications: INTECH Open Access Publisher, 2008.

[8] Ulmen, J. and Cutkosky, M. R., “A robust, low-cost and low-noise artificial skin for human-friendly robots,” in ICRA, 2010, pp. 4836-4841.

[9] Yussof, H., Wada, J., and Ohka, M., 2010, “Sensorization of robotic hand using optical three-axis tactile sensor: evaluation with grasping and twisting motions.“

[10] Vatani, M., Lu, Y., Engeberg, E. D., and Choi, J. W., 2015, “Combined 3D printing technologies and material for fabrication of tactile sensors,” International Journal of Precision Engineering and Manufacturing, Vol. 16, No. 7, pp. 1375-1383.

[11] Dahiya, R. S., Metta, G., Cannata, G., and Valle, M., 2011, “Guest editorial special issue on robotic sense of touch,” IEEE Transactions on Robotics, Vol. 27, No. 3, pp. 385-388.

[12] Schmidt, P. A., Maël, E., and Würtz, R. P., 2006, “A sensor for dynamic tactile information with applications in human–robot interaction and object exploration,” Robotics and Autonomous Systems, Vol. 54, No. 12, pp. 1005-1014.

[13] Kerpa, O., Weiss, K., and Worn, H., “Development of a flexible tactile sensor system for a humanoid robot,” in Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on, 2003, pp. 1-6.

[14] Maheshwari, V. and Saraf, R., 2008, “Tactile devices to sense touch on a par with a human finger,” Angewandte Chemie International Edition, Vol. 47, No. 41, pp. 7808-7826.

[15] Vatani, M., Engeberg, E. D., and Choi, J.-W., 2015, “Conformal direct-print of piezoresistive polymer/nanocomposites for compliant multi-layer tactile sensors,” Additive Manufacturing, Vol. 7, pp. 73-82.

[16] Vatani, M., Engeberg, E. D., and Choi, J. W., 2014, “Detection of the position, direction and speed of sliding contact with a multi-layer compliant tactile sensor fabricated using direct-print technology,” Smart Materials and Structures, Vol. 23, No. 9, pp. 1-11.

[17] Choi, J.-W., Kim, H.-C., and Wicker, R., 2011, “Multi-material stereolithography,” Journal of Materials Processing Technology, Vol. 211, No. 3, pp. 318-328.

[18] Lu, Y., Vatani, M., and Choi, J.-W., 2013,

"Direct-write/cure conductive polymer nanocomposites for 3D structural electronics," Journal of Mechanical Science and Technology, Vol. 27, No. 10, pp. 2929-2934.

[19] Akasaka, T., Wudl, F., and Nagase, S., Chemistry of nanocarbons: John Wiley & Sons, 2010.

[20] Someya, T., Kato, Y., Sekitani, T., Iba, S., Noguchi, Y., Murase, Y., Kawaguchi, H., and Sakurai, T., 2005, "Conformable, flexible, large-area networks of pressure and thermal sensors with organic transistor active matrixes," Proceedings of the National Academy of Sciences of the United States of America, Vol. 102, No. 35, pp. 12321-12325.

[21] Vatani, M., Engeberg, E. D., and Choi, J.-W., 2013, "Force and slip detection with direct-write compliant tactile sensors using multi-walled carbon nanotube/polymer composites," Sensors and Actuators A: physical, Vol. 195, pp. 90-97.

[22] Heo, J.-S., Kim, J.-Y., and Lee, J.-J., "Tactile sensors using the distributed optical fiber sensors," in 2008 3rd International Conference on Sensing Technology, 2008, pp. 486-490.

[23] Su, Z., Hausman, K., Chebotar, Y., Molchanov, A., Loeb, G. E., Sukhatme, G. S., and Schaal, S., "Force estimation and slip detection/ classification for grip control using a biomimetic tactile sensor," in Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on, 2015, pp. 297-303.

[24] Dahiya, R. S., Lorenzelli, L., Metta, G., and Valle, M., "POSFET devices based tactile sensing arrays," in Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on, 2010, pp. 893-896.

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