Low-Cost Sensor-Rich Fluidic Elastomer Actuators Embedded with Paper Electronics

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Fluidic elastomer actuators (FEAs) are popular actuation ways in soft robotics due to their low cost and simple fabrication process. To realize intelligent soft robotic systems, real-time monitoring of their deformation and interactions with surrounding objects including shape and proximity is important. Thus, integration of sensors into FEAs while considering cost reduction and mass production is required. Because paper features low cost and recyclability, herein, two paper-based sensors, resistive strain sensors (RSSs) and capacitive proximity sensors (CPSs), are incorporated into FEAs as the strain-limiting layers. The RSS exhibits the ability to detect the actuated bending angle with hysteresis $\approx 0.01\%$ and high repeatability for 30 cycles. The RSS is also able to detect different object sizes being grasped by the FEA. In contrast, the CPS starts detecting object proximity 8 mm away from the sensor surface and functions well at various approaching speeds. The CPS is also capable of distinguishing objects of different materials by their permittivity. Finally, an intelligent soft gripper which carries these two sensors is demonstrated, where bending curvature, object proximity, contact, and release are monitored in real time. The results provide a pathway for the development of low-cost sensorized soft robotic systems with advanced sensing functionalities.

In recent years, soft robotics has been an emerging field due to its great potential in applications such as human assistance, grippers and manipulators, and biomimetic robots. Of diverse actuation technologies for soft robots, fluidic elastomer actuators (FEAs) are widely used due to their structural robustness, low-cost materials, and simple fabrication process. FEAs are made of compliant materials like silicone elastomers and consist of a series of embedded chambers and channels. Those chambers inflate when pressurized by gas or liquid, leading to deformation of the entire structure. The characteristics of the deformation depend on the architecture and materials of the actuator. For example, an inextensible material such as paper is often used as a strain-limiting layer to produce bending actuation. A great number of studies have investigated material selection, fabrication methods, and device geometries to improve the performance of FEAs and their dexterity.

For practical operation of FEAs in soft robotic systems, real-time detection of their deformation and surrounding environment is crucially important. For this, FEAs are required to be integrated with diverse sensors which have to be soft or flexible enough to be adaptively deformed in FEAs without fracture or delamination. Previous studies have reported great advances in compliant sensor-embedded FEAs with the main focus on strain sensing to detect curvature change during actuation or obtain contact information with objects. However, in these studies, sensors are often commercially provided or produced by complicated fabrication processes, which would make the actuator costly and limit the potential for mass production. Moreover, because the sensors are integrated as independent elements, the structure of the actuator tends to get complicated. For mass production and reduction of fabrication cost, manufacturing processes and device architecture for such sensor integration should be more compatible with existing processes of FEAs.

Here, we present a low-cost and multifunctional sensor-embedded FEA that has two types of printed sensors on a single paper substrate: resistive strain sensor (RSS) and capacitive proximity sensor (CPS). As a substrate, the paper is cheap, recyclable, and allows printing of conductive materials on it, which is suitable for low-cost, large-area, and batch fabrication. These sensing elements are printed using inkjet printing, a popular method in paper electronics (PE). Apart from sensing, the paper substrate also acts as the strain-limiting layer in the actuator, as discussed in other studies. Therefore, the printing sensor pattern on paper is a highly compatible and simplest way to provide sensing functionalities to FEAs with the minimized additional
element. PE has been widely studied in the past decade for the development of flexible and recyclable devices.\textsuperscript{[26–32]} The fabrication of the PE device is simple and rapid, which can also be done using a commercial office printer, implying that this strategy is promising for mass production.\textsuperscript{[26]} However, attempts have yet been made on integrating PE to FEAs. Incorporating the two sensors, RSS and CPS, enables FEAs to simultaneously acquire rich information: deformation of the actuators, shape of the external object, proximity, and type of material in contact. Fabrication of the sensor part is rapid and arbitrary geometry can be patterned. We characterize an FEA embedded with RSS and CPS to thoroughly examine the feasibility of integrating PE into actuators of this type. We then demonstrate an intelligent soft robotic gripper consisting of the two sensorized FEAs capable of detecting proximity to the object, its shape, and types of material.

PE-sensor-embedded FEA developed in this study is shown in Figure 1. As shown in Figure 1a, on the paper substrate, the RSS region has a zig-zag electrode pattern, whereas the CPS region has an interdigitated electrode pattern. They are patterned on a paper substrate using a commercial inkjet printer which allows batch fabrication of the sensing substrates (Figure 1b). Nanosilver ink is used as a conductive material for the electrodes. Figure 1c shows the cross-sectional view and dimensions of the PE-FEA, where the sensing substrate is embedded as a strain-limiting layer. The sensing layer is placed in such way so that the electrodes face the outside of the actuator structure (Figure 1d). A silicone elastomer (Ecoflex 00-30, Smooth-on) is used for the main body of the FEA. Under pressurization, the chambers are inflated and push together, leading to bending deformation of the entire structure (Figure 1e,f). In a preliminary test, the actuator was able to withstand numerous actuated cycles and no delamination of the PE part was observed.

Figure 2 shows the working principles of RSS, CPS, and PE-FEA. The RSS has a single, continuous serpentine-like electrode, whose resistance changes as the paper substrate is bent, as shown in Figure 2a. Thus, the resistance of the nanosilver wire is obtained from

$$R = \frac{\rho l}{A}$$

where $\rho$ is resistivity, $A$ is the cross-sectional area of the nanosilver wire, and $l$ is the length of the nanosilver wire. As bent, the electrode is compressed, resulting in $l$ reducing and $A$ increasing based on the Poisson effect. Therefore, the change in the resistance of the RSS can be used to estimate the bending angle. As for the CPS, which is arranged in an interdigitated shape, opposite electric charges are generated on neighboring electrodes and an electric field is formed in between, generating a series of coplanar capacitors, as shown in Figure 2b. As an object (e.g., finger) approaches the CPS surface, the electric field is interfered. As a result, the capacitance changes, which allows us to detect the proximity of objects. Figure 2c shows how an intelligent FEA, embedded with on-paper RSS and CPS as the strain-limiting layer, works to detect the bending angle and the object proximity.

Figure 3a shows the change in the electrical resistance of the RSS part in PE-FEA when increasing the actuated bending angle. The resistance values were normalized with respect to the initial

![Figure 1](image1.png)

**Figure 1.** Integration of paper sensors (PE) and FEA. a) Layout and pattern of RSS and CPS on paper. b) Printing process of the sensing paper substrate. c) Cross-sectional view and dimensions of the PE-FEA where the sensing paper substrate is embedded as a strain-limiting layer. d) PE-FEA developed in this study. e) PE-FEA in the initial (i.e., unpressurized) state and f) pressurized state.
value where no pressure is applied to the actuator. As the actuated bending angle increased, the resistance successively decreased roughly following a linear function with \( R^2 \approx 0.996 \), whereas the resistance was increased back to near its original value with recovering the actuator. In the recovering cycle, the RSS exhibited a non-linear response when resulting hysteresis at the final state was 0.01%. To confirm whether the hysteretic behavior was attributed to the integration with FEA, RSS samples without being embedded into FEA were tested, as shown in Figure 3b. Hysteresis was also observed, implying that this characteristic in the RSS was not mainly attributed to the integration with FEA. The hysteretic behavior has been found in many printed resistance strain sensors that used nanosilver ink.[4,32] Although the reason for the hysteresis is still unclear and needs further investigation, the data obtained by the fabricated RSS are considered reliable and repeatable due to a high consistency in

Figure 2. Working principles of a) RSS, b) CPS, and c) PE-FEA.

Figure 3. a) Change in resistance of RSS part in the PE-FEA. b) Change in resistance of only RSS with bending. c) Difference in resistance when PE-FEA grasped acrylic disk with different curvatures. Right photographs show how the PE-FEA was used to measure object sizes. The resistances in parts (a)–(c) are normalized with respect to the initial resistance (i.e., before actuation).
resistance, about 30 times. Thanks to the high sensitivity to the actuated bending angle, the RSS in PE-FEA was then characterized for detecting objects of different sizes (i.e., different curvatures). In this characterization, four acrylic disks with curvatures of 20.0, 23.0, 26.7, and 40 (m⁻¹) were used, as shown in Figure 3c. The measured resistance values obtained through the RSS were linearly decreased with increasing curvature (i.e., decreasing the disk radius), which is in good agreement with the results shown in Figure 3a. These results suggest that the RSS was able to measure the bending angle of the actuator, as well as the grasped object size.

It should be noted that the composition, surface chemical condition, and morphology of paper greatly affect characteristics of printed nanosilver electrodes, such as electrical performance including hysteresis and patterning accuracy. We chose a resin-coated paper (NB-RC-3GR120, Mitsubishi Paper Mills) due to its excellent compatibility and good adhesion to silver nanoparticles. We also confirmed that nanosilver electrodes on this type of paper had a high structural integrity and low electrical resistance.

We then characterized the CPS part in PE-FEA. It has been reported that the sensitivity of the capacitance proximity sensor varies with the sensor geometrical layout; here, the influence of the electrode width (w) and pitch (p) should be verified. The sensitivity of the CPS can be presented as the slope of the capacitance–distance curves. Figure 4 shows the variation in capacitance when an object (i.e., a hand finger) approaches the CPS with variable electrode widths and pitches. For this investigation, the CPS-FEA device was put on a table and then was approached by a finger that was put on a linear translation stage. Each time after moving the finger, a moving-average capacitance was measured within 30 s. For the CPS samples with a fixed width of 800 μm, the initial capacitance and sensitivity were increased when decreasing the electrode pitch, as shown in Figure 4a. The sample with the electrode pitch of 300 μm possessed the best sensitivity, where the capacitance started to increase at a distance of 8 mm away from the finger and dramatically increased roughly following an exponential function. For the samples with a fixed electrode pitch of 300 μm, sensitivity barely showed change with varying the electrode width, but the initial capacitance value increased for the smaller electrode width, as shown in Figure 4b. These results indicate that the electrode pitch was relatively dominant to the sensitivity of CPS compared with the electrode width. Thus, the CPS pattern with a pitch of 300 μm and a width of 500 μm was used in the following experiments.

Figure 5a shows the change in capacitance of the CPS when approaching a finger at different actuation rates (Γ), which was evaluated in terms of the curvature change per second (m⁻¹ s⁻¹). This investigation was to simulate common practical situations where FEA is used to grasp objects at variable approaching speeds. As shown in Figure 5b, the capacitance gradually increased, following an exponential-like behavior when the actuator was slowly actuated (Γ: 5.718 m⁻¹ s⁻¹), which is similar to the trend in Figure 4. When the actuation rate increased, the exponentially increasing behavior started to disappear and the capacitance demonstrated an abrupt jump-up within a shorter time before contact with the objects, as shown in Figure 5c (Γ: 7.718 m⁻¹ s⁻¹). This implies that the response time of the nanosilver proximity sensor varied with the approaching speed; the faster the approaching speed, the shorter the response time. However, the object proximity was still able to be detected even at a very high actuation rate (Γ: 25.307 m⁻¹ s⁻¹), as shown in Figure 5d. After contact with the objects, the capacitance kept increasing with time, which might be attributed to the fact that the electric field between electrodes passed through a medium with a larger permittivity (i.e., hand) and the contact area increased with time due to compression.

When in contact with an object, the capacitance value of the CPS part in PE-FEA changes according to the relative permittivity of the target material that acts as additional dielectric between the electrodes of the CPS. This behavior can be used in soft fingers for recognizing the material type of the object being touched or grasped. We investigated the sensing ability of the CPS for different material types. As shown in Figure 6a, films of polyimide, aluminum, and copper were placed on a glass bottle, and then the PE-FEA was actuated to make it come in contact with each material including the surface of the bottle. Figure 6b shows the result as the capacitive change before and after touching the materials. For dielectric materials, the capacitive change of the CPS

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Influence of the electrode pitch and width on the distance measurement by the CPS. The distance of zero means the surface of CPS. a) Fixed electrode width but different pitches. b) Fixed electrode pitch but different widths.
reflected their relative permittivity: 2.2% for polyimide ($\varepsilon_r = 3.4$) and 4.3% for glass ($\varepsilon_r = 3.4$–10.0). For conductive materials, the sensor response was higher compared with the case of the dielectrics: 12.0% for aluminum and 12.4% for copper. The capacitive changes in these two metals are almost the same because the dielectric constant of conductor is theoretically infinite. The result suggests that the CPS part in PE-FEA is capable of distinguishing dielectrics of different relative permittivity and conductors.

On the basis of the results described previously, we finally demonstrate an application example by an intelligent soft gripper, exploiting the sensing abilities of the RSS and CPS, which can detect the bending angle of the actuator, object proximity, and contact. Figure 7 shows the change of capacitance and resistance during the grasping and release process (see also Movie S1, Supporting Information). As the PE-FEA started to bend at 5.5 s, the resistance started to decrease correspondingly. The capacitance did not change at this moment because the finger was still too far to be detected. As the time reached about 15.5 s, the finger became detectable by the left actuator, whereas it could still not be detected by the right actuator. When the time reached 19.3 s, the right actuator could detect the finger. The capacitance shows an abrupt increase due to contact with the finger at about 22.7 s, followed by a continuous decrease after reaching a peak. Because the contact area between the CPS and finger changed, the capacitance varied correspondingly. When the actuator totally released the finger, the declining curve of capacitance showed a change in slope. It should be noted that in the whole operation, the actuation speed of PE-FEA was mainly limited by the performance of the external pump. Therefore, using pumps with a high output will significantly increase the actuation rate, as shown in the literature.[10] In addition, optimization of the FEA architecture can be taken into consideration. Even so, these results indicate that the PE-FEA worked well as an intelligent soft gripper, showing the high potential of our solution for sensorized soft robotic systems.

This work demonstrates the successful integration of PE with FEA to enable low-cost highly sensorized soft actuators.
A PE-FEA was developed, in which RSS showed a linear decreasing behavior with bending the actuator, whereas it exhibited a nonlinear increasing behavior with recovering the actuator, resulting in hysteresis at ~0.01% at the final state. The measured bending angles were considered highly reliable due to a high consistency at about 30 times. The RSS was also able to measure the size of objects that it grasped. As for the CPS part in PE-FEA, the sensor geometry was experimentally determined to be an interdigitated shape with a pitch of 300 μm and a width of 500 μm for the best sensitivity. The CPS was capable of measuring the object proximity even with a high actuation rate of 25.307 (m/s). Finally, an intelligent soft gripper that incorporated the RSS and CPS was demonstrated, which enabled real-time monitoring of bending, proximity, and contact during the grasping and releasing process. Although the influences of the paper substrate on the performances of RSS and CPS are out of the scope of this study, related investigations will be necessary to be conducted in future work. The proposed strategy of PE-FEA is expected to be applied to low-cost and mass-producible fabrication for intelligent and versatile soft robotic systems in various forms.

**Experimental Section**

Fabrication of PE-Sensor-Embedded FEA: A commercial inkjet printer (MG7530, Canon) was used to print sensor patterns on paper. Through the printer, a nanosilver ink (NBSIJ-MU01, Mitsubishi Paper Mills) was deposited into the designed sensor patterns on a resin-coated paper (NB-RC-3GR120, Mitsubishi Paper Mills). Molding of elastomer was used to fabricate FEA. The molding parts were produced using a 3D printer (Ultimaker 3 Extended, Ultimaker). A silicone elastomer (Ecoflex 00-30, Smooth-on) was used for the main body of FEA. After mixing with the manufacturer’s recommended ratio, the elastomer was poured into the top molds, immediately followed by degassing in a vacuum chamber to ensure that no air bubble was left inside the casted silicone structure. The silicone was cured at room temperature for 4 h. A thin silicone layer for the base part of the FEA was also fabricated using the same procedure. Upon degassing, a paper substrate carrying a set of RSS and CPS was lightly put onto the thin silicone layer, and they were bonded together by curing. Finally, the remaining part of the base layer was filled with silicone, and the main body of the actuator was then settled into the uncured silicone of the base layer such that they were sealed and connected together. The actuator was 61 mm long and consisted of six chambers arranged in parallel with the length direction of FEA. The wall of each chamber was 1 mm thick and the separation between each chamber was 2 mm.

Characterization of PE-Sensor-Embedded FEA: To characterize PE-FEA, we built a control panel, which consisted of a compressor, a pressure sensor, an electromagnetic valve, and a microcontroller that was used to actuate PE-FEA by controlling pressurized air. The entire system was established based on an open-source setup design, as discussed in a previous study. A high-resolution camera (L-835, HOZAN) was used to record the deformation of PE-FEA under different applied pressures. The electrical resistance of RSS with bending, as well as the capacitance of CPS with approaching objects, was measured using an LCR meter (LCR-6002, GWInstek) that operated at a frequency of 1 kHz.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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