Development of an Artificial Fingertip with a High-Sensitivity 3-Axis Force Tactile Sensor Embedded for Robotic Hands

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***Abstract*— Advanced robotics engineering, which is gaining attention as a solution to the decline in the labor force, still faces a major challenge due to its immature object manipulation capabilities. Hence, our research team introduces an artificial robotic fingertip equipped with a highly sensitive tri-axial force tactile sensor, designed to enhance the object manipulation capabilities of robots. The tri-axial force sensor array embedded in the fingertip features a hybrid structure that combines the high sensitivity of single-crystal silicon with the excellent mechanical properties of polymer-based rubber. Through a series of evaluations, the developed sensor demonstrated linear output within a measurable range (~1.2 N), high sensitivity, and outstanding fundamental characteristics, such as low hysteresis and repeatability errors. Furthermore, it exhibited the ability to detect forces along each of the three axes independently, without mutual interference.**

Keywords-tactile sensor; dexterous manipulation; robotic hand.

I. INTRODUCTION

Gerontechnology is a portmanteau of "gerontology" and "technology," referring to technologies that address the societal issue of aging populations in modern society [1]. Representative examples include healthcare, advanced robotics engineering, and the Internet of Things (IoT). In particular, research on developing service robots that can ultimately perform tasks on behalf of people is drawing significant interest. However, current robots are limited to performing monotonous tasks like object delivery due to their inadequate object manipulation abilities. In contrast, humans can delicately manipulate objects, detecting slips and preventing them from falling, and even peel tender objects like grapes. This ability arises because, unlike robots that rely solely on vision, humans simultaneously utilize tactile sensation, allowing them to detect various physical quantities generated by the movement of objects in contact with the skin, in addition to vision. Thus, significant research is being conducted to develop tactile sensors that mimic human tactile sensing capabilities, with the aim of enhancing the object manipulation abilities of robots. However, there are still challenges in developing tactile sensors that meet all the requirements (such as high sensitivity, excellent durability, low hysteresis error, etc.) [2]. Therefore, our research team would like to propose a highly sensitive tri-axial force tactile sensor array applicable to an artificial fingertip by merging the excellent sensing capabilities of silicon-based strain gauges with the superb mechanical properties of polymer-based rubber. The rest of the paper is organized as follows: In Section II, we present the design and fabrication process of the device. In Section III, we present the results from the sensor evaluation, and finally, we conclude the paper in Section IV.

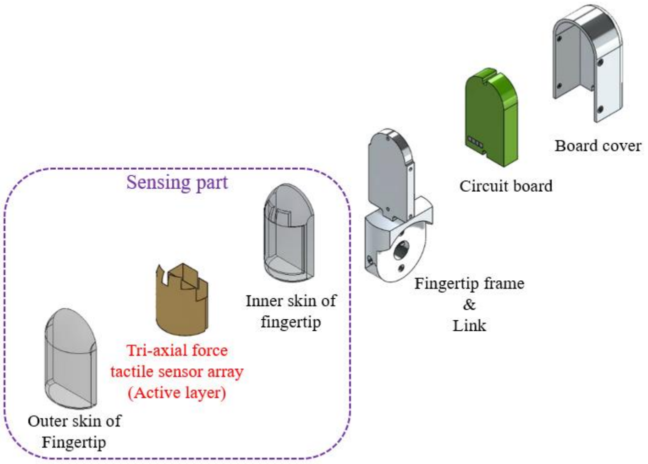

Figure 1. 3D Exploded view of the designed artificial robot fingertip.

II. DESIGN & FABRICATION

We designed an artificial fingertip with a highly sensitive tri-axial force sensor array based on the strain gauge. The fingertip comprises a sensing part at the front and a circuit board at the back, centered around the fingertip frame, as detailed in Figure 1. The sensing part consists of a tri-axial force sensor array (active layer) and the inner and outer skin of the fingertip. The tri-axial force sensor array is composed of 12 cells (48 gauges), each comprising four U-shaped strain gauges based on single-crystal silicon nanomembranes. As illustrated in Figure 2, to ensure detection of the tri-axial force distribution across the entire fingertip area, the 12 cells were strategically positioned. The inner skin of the fingertip is positioned beneath the tri-axial force sensor array to

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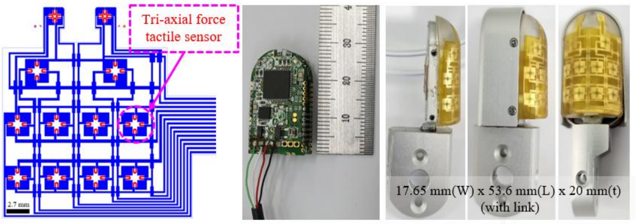

(a) (b) (c)

Figure 2. (a) CAD drawing of a tri-axial force tactile sensor array (b) Picture of the circuit board for embedding an artificial fingertip (c) Photograph of the artificial fingertip integrating core technologies.

induce mechanical deformation of the active layer in response to external forces, resulting in resistance changes in the strain gauges. As such, PDMS (Polydimethylsiloxane), which has excellent deformation properties under external forces, was used, and the inner skin was fabricated using a 10:1 (base: curing agent) mixing ratio of PDMS. Considering the assembly process, the outer skin is designed with 10:1 PDMS for ease of integration with the inner skin. As a result, we devised an artificial fingertip with a highly sensitive three-axis force sensor array based on the sensing part that can have both the high-sensitivity characteristics of single-crystal silicon and the mechanical flexibility of PDMS. To accommodate the circuit board within the robot's fingertip, which is similar in size to a human finger, it was designed with a two-layer structure and was developed to process the signals of 48 strain gauges through a zero-potential method using a DC source. The dimension of the circuit board is 17 mm (W) x 25 mm (H) x 8 mm (t). The fabrication process of the artificial fingertip consists of a process for manufacturing the sensing part through MEMS processes for the production of the active layer and casting processes for the PDMS layers, and an integration process for assembling the manufactured sensing part and a circuit board. Based on processes established in previous research [3], the active layer and PDMS layers were fabricated. The circuit board and fabricated artificial fingertip are shown in Figure 2.

III. EVALUATION

To evaluate the sensing capability of the sensor, the artificial fingertip embedded with the tri-axial force sensor array was positioned on a tri-axial force measurement stage [4]. A metal tip with a diameter of 1 mm was aligned with the center of a single cell, and the changes in gauge output were analyzed as the metal tip was lowered in the vertical direction to measure the normal force sensing characteristics of the sensor. The results showed linear output characteristics within a range of 1.2 N, and superb sensitivity sufficient to detect forces as low as 10 mN. Furthermore, by incrementally increasing and decreasing the load by 0.2 N in each step within the linear output range, the sensor exhibited less than 3% hysteresis error. Also, repeatability error was less than 3% based on 1000 repeated measurements at each step. Next, to evaluate the sensor's performance in detecting shear forces, the output characteristics of the sensor were analyzed as the tip was moved in the X-axis direction by 10 μm increments with a pre-load of 0.15 N applied to a single cell. As a result, the output of the forces in the Z- and Y-axis directions showed little change, and the cross-talk error, an associated indicator, was less than 3%. Mechanical characteristics of the sensor are shown in Figure 3, and the calculation equations for analyzing the output characteristics of the gauge are presented in previous studies [3][4].

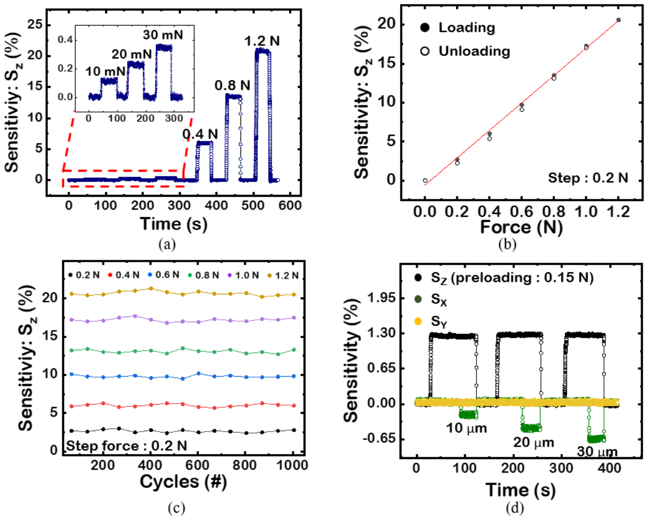

Fig 3. Mechanical characteristics of the tri-axial force tactile sensor array (a) Sensing range & resolution (b) Hysteresis characteristics (c) Repeatability data (d) Tri-axial force output.

IV. CONCLUSION

Our research team has introduced a highly sensitive tri-axial force tactile sensor array composed of 12 cells that can be embedded in the anthropomorphic fingertip. The tactile sensor showed nearly linear output characteristics for the normal force of 1.2 N or less and was sensitive enough to distinguish the load of 0.1 mN. The hysteresis and repeatability characteristics, fundamental sensing characteristics of the device, exhibited errors of less than 3%. It was demonstrated that forces along tri-axial directions could be detected independently, without mutual interference. In the near future, we plan to conduct experiments to verify whether our anthropomorphic fingertips integrated into a robotic hand can detect the tri-axial force distribution generated by objects when manipulating them in various grasping states. Furthermore, by developing a large-area sensor that can be applied to the entire robot hand, we intend to implement an intelligent robot hand with tactile sensing capabilities similar to human hands.

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