3D Printed Robotic Hand with Embedded Touch Sensors

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***Abstract*—This paper presents a 3D printed robotic hand designed to have two capacitive touch sensors embedded in the distal phalanges of the fingers. Additionally, the readout electronics have been designed and fabricated to obtain the digital values of the capacitances and to use this data for touch feedback control. The touch or pressure sensors were fabricated by 3D printed electrodes using copper based conductive filament and a two part-rubber as the dielectric. The sensitive fingertip was tested with dynamic and static stimuli and the average sensitivity of the sensors was found to be 0.6%N^{-1}. The proof-of-concept robot hand developed here shows that the concept could be applied to develop the 3D printed embedded sensorised systems or instrumented objects needed for applications such as internet of things and human-computer interaction.**

Keywords—Soft Robotics, Embedded Sensors, Tactile Sensors, 3D printing, Additive Manufacturing

I. Introduction

Tightly coupled sensing, actuation, and computation into soft 3D structures could enable a new generation of truly smart and complex systems that have human-like dexterity, motor skills, and physical abilities [1-5]. The field of robotics has strived to replicate these capabilities through large area conformable electronic skin (eSkin) [6-11], which are placed on the external surface of the robot's body. Likewise, wearable systems and tattoo-like eSkins have benefited the field of health monitoring [12, 13]. However, most of these conformable eSkins come with the challenge of wear and tear during frequent use [14]. The routing of large amount of wires connecting the sensors and the readout electronics is another challenge, especially in highly dense areas with limited space, of e-skins [8, 9, 15-17]. Here, we demonstrate a new approach to address these traditional issues by embedding the two capacitive touch sensors in the distal phalanges of a 3D printed robotic hand (Fig. 1). This paper extends other works related to this area where only one sensor with the readout circuit is embedded inside the fingertip [14]. The developed sensorised fingertips are robust, show stable response and are affordable. Compared to other works where embedded off-the-shelf sensors have been reported [14, 18-21], the fingertip presented here have intrinsic sensors realised by fully 3D printing. The presented facile approach has the potential to be scaled up to large-area manufacturing.

The new methods for embedded sensor system presented here could enable manufacturing of advanced and complex designs, especially with additive manufacturing technologies. In particular, Fused Deposition Modeling (FDM) 3D printing is commonly used to fabricate rigid parts as decorated structures and in some cases for mechanical components. In recent years, the automotive, aeronautic and medical industries are using such system as one of their manufacturing processes [22-26]. The field is now exploring how to extend the capabilities of FDM printers utilizing flexible/bendable materials, composited filaments and custom-made Direct Ink Writing (DIW) extruders, which are capable of printing conductive lines to enable new designs, ideas and products [14, 19, 27-29]. Several devices have been developed benefiting from such advantages to overcome challenges inherited from other fabrication processes. Embedded tactile sensors, antennas, 3D circuits and embedded electronics are some of the devices that are using such technologies [22, 27, 30-32]. This work extends this trend with the development of two embedded pressure sensors integrated in the interior of the distal phalanx of a robotic thumb and the associated readout printed circuit board (PCB) to identify the differential pressure between the right and left side of the phalanx. Multimaterial 3D printing (i.e. printing plastic as well as conductive materials) is also the distinct feature of this work.

This paper is organised as follows: Section II describes the design of the sensing finger, the fabrication process of the device and the electronics of the system. Section III explains the experiment process, the results, evaluation of the sensors' performance and presents the working prototype. Section IV summarizes the results and presents an overview of the study.

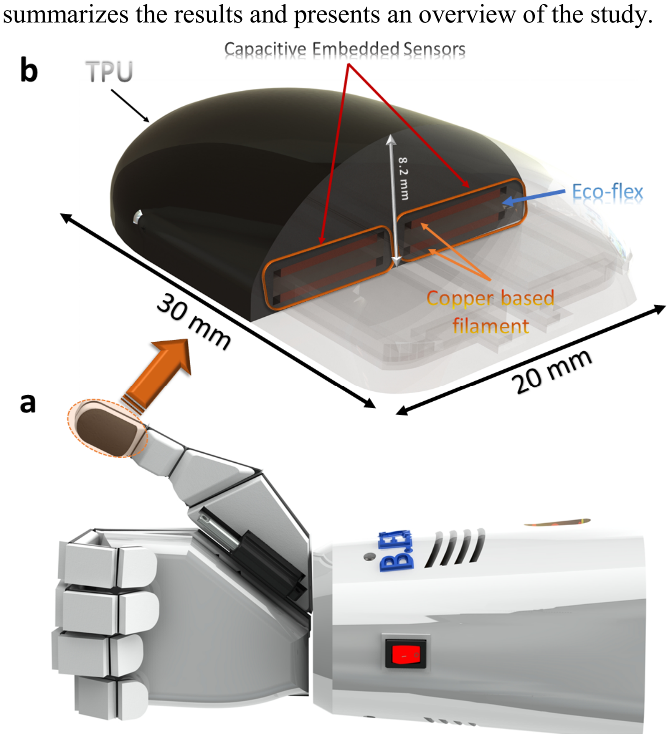

Fig. 1. a) CAD Design of robotic hand with fingertip having embedded soft capavitice sensors. b) Cross-Sectional view of the soft sensing fingertip.

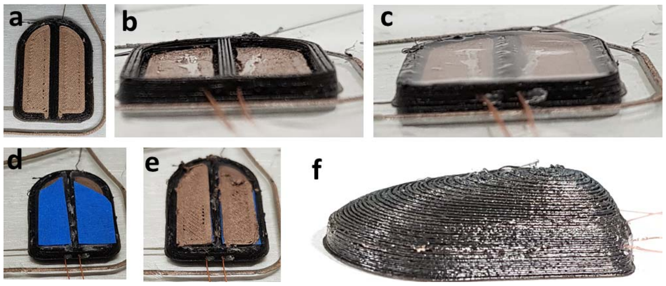

Fig. 2. Fabrication steps of the soft capacitive sensing fingertip. a) bottom electrodes. b) Formation of the cavity for the dielectric. c) electrode-dielectric structure. d) adhesive tape on top of the dielectric. e) Deposition of the top electrodes. f) Soft-embedded capacitive pressure sensing finger tip.

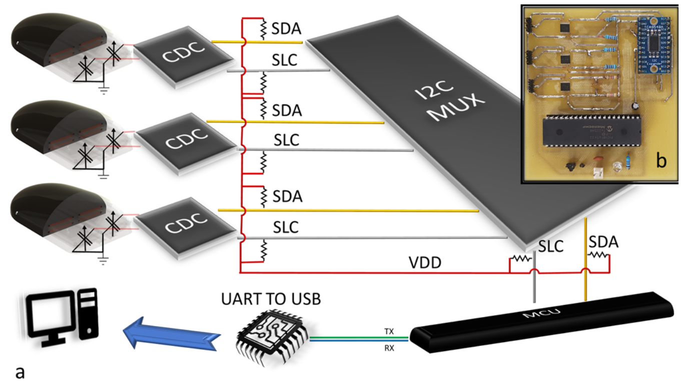

Fig. 3. a) Schematic of the system b) Fabricated PCB for reading capacitance value and transmission of digital data.

II. Materials and Methods

A. Design of the embedded soft finger-tip

In this work, we present the thumb fingertip with two soft embedded capacitive pressure sensors used as a feedback system to understand the distribution of an applied force on top of the distal phalanx of a robotic hand (Fig. 1a). The device was designed in a Computer Aided Design (CAD) software. The sensing phalanx resembles the human fingertip of the thumb with two soft capacitive sensors located inside, as shown in Fig. 1b. The entire device is 20 mm wide, 30 mm long and 8.3 mm thick. The overlapping areas of the parallel capacitive sensors are 163.24 mm^2 with a dielectric thickness of 1 mm. The capacitive sensors have 2.5 mm distance and are located at 5.8 mm depth inside the highest point of the fingertip. The parallel plates are 0.5 mm thick and a 0.25 mm offset from the walls of the designated cavities to eliminate the chances of bridging with each other during the fabrication process.

B. Fabrication

The 3D printing materials used in this study are chosen for their bendability and softness. The electrodes of the capacitive sensors are made from copper based composite filament (electrifi, Multi3D) and the dielectric material was formed by a two part-rubber material (Ecoflex 00-30). The rest of the fingertip was fabricated with a Thermoplastic polyurethane (TPU) filament (NinjaFlex, NinjaTek). The TPU filament was used as it could provide softness similar to the human skin. The electrifi filament has showed good electrical characteristic and robustness under bending conditions [33]. The two-part rubber has been commonly used in other studies as part of the transducer [14, 34-36].

All fabrication steps took place on an Ultimaker S5. The printer was mounted with the TPU filament on the first nozzle and Electrifi on the second. The device was printed with 0.2 mm layer height, and printing speed of 15 mm/s from the two 0.4 mm diameter nozzles. The infill of the TPU was 45% and the conductive filament was 100% with printing temperatures of 230 ^{o}C and 150 ^{o}C respectively. The 45% infill of the TPU was found to allow some compressibility to further enhance the grasping capabilities of the fingertip. The entire fabrication process took approximately 3 hours including curing and wire bonding.

The fabrication started with the printer depositing TPU layer by layer. On the third printed layer, the second nozzle mounted with the conductive filament formed the bottom electrodes of the device. The Gcode was modified to pause on the 4^{th} layer of the print to allow the wiring of the electrodes (Fig. 2a). Once the wire bonding was done the print was resumed until the 10^{th} layer, where the printer formed the two cavities dedicated to the dielectric material (Fig. 2b). The two part-rubber was mixed in a 1:1 ratio and stirred for 15 mins. The mixture was poured on top of the cavities and cured for 20 minutes, thus forming the electrode-dielectric structure (Fig. 2c). Once the dielectric was fully cured, a blue scotch masking tape (RS Components) was cut with the shape of the electrodes and placed on top of the dielectric. This step is required in order to enable the printing of the conductive material on top of the dielectric as the adhesion between the two-part rubber and the filament is poor (Fig. 2d). On the 13^{th} layer, the printer was paused for the last time for the wire bonding of the top electrodes (Fig. 2e) and once completed the print was resumed. Fig. 2f shows the fabricated device.

C. Electronic Readout

Based on the device characteristics, a PCB was fabricated and assembled to demonstrate the capability of presented system in terms of providing the touch feedback to an anthropomorphic robotic end-effector. Fig. 3a shows the schematic of the system and Fig. 3b shows the fabricated PCB dedicated to the capacitive readout electronics. The system uses a microcontroller (μC) to communicate with several Capacitance to Digital Converters (CDC) Integrated Circuits (ICs) via Inter-Integrated Circuit (I^2C) communication protocol. An I^2C multiplexer (MUX) is used to communicate with several CDCs, due to the fact they have the same I^2C IPs. This arrangement was done to expand to multiple sensing fingertips. The CDCs are able to convert the capacitance value from the sensors to digital data and transmit back the data to the μC. The microcontroller is connected to a Universal Asynchronous Receiver/Transmitter (UART) to Universal Serial Bus (USB) converter. The μC transmits the data from UART to the USB converter and then to a Personal Computer via USB cable, where the data are displayed on a LabVIEW program. The CDC converters have two inputs for capacitive sensors and can operate in a single-ended or differential mode. Here, we are mostly interested in the distribution of the force and therefore differential mode was desired and enabled from the CDC's registry.

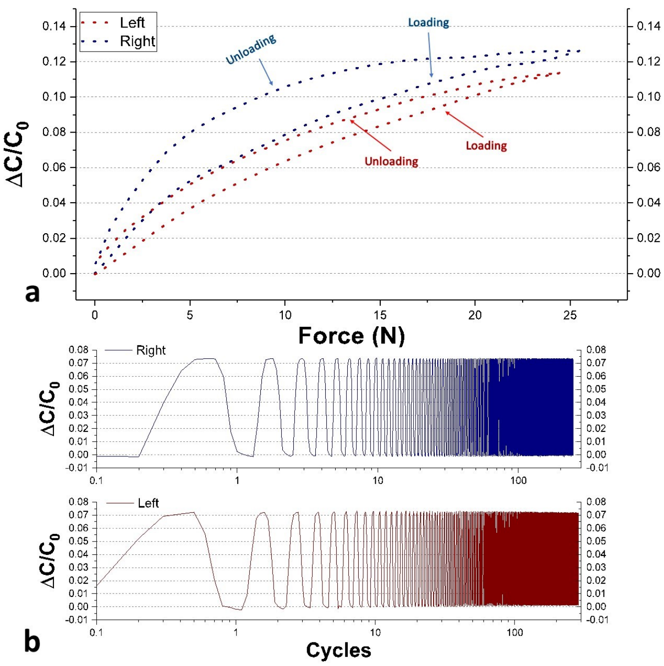

Fig. 4. a) Relative change of capacitance with respect to static force. b) Relative change of capacitance of the two sensors over time.

III. Results and Discussion

A. Performance and Evaluation

The sensor system was tested under static and dynamic condition. Fig. 4a shows the relative change of capacitance with respect to force for the two sensors. The devices were examined under linear loading, up to 25 N, and linear unloading, down to 0 N. From that experiment, the hysteresis graphs were obtained for two sensors. Likewise, the sensors were loaded and unloaded from 0 N up to 15 N for more than 200 cycles at a frequency of 1 cycle/s. The results revealed that both transducers have similar response and have high repeatability. Fig. 4b presents the relative change of capacitance with respect to cycle.

The left sensor has a nominal capacity of 3.933 pF while the right sensor is 4.471 pF. The sensitivity of the left sensor is 0.005523 per N with linear fit of 92.2% for the entire test range (0 N-25 N). The right sensor showed similar characteristics with sensitivity of 0.00657 per N, but slightly less linear response with linear fit of 64%. Table 1 compares this work with other related works. The right sensor showed slightly higher sensitivity, but in contrast it showed a slightly larger amount of hysteresis. These variations could be due to minor imperfections related to dielectric deposition, as the drop casting process could cause uniformities. Due to the comparable responses of the two sensors, their integration on a robotic hand does not require any sophisticated hardware compensation.

TABLE I. Comparative Table

Work	***Sensitivity***	***Cycles***
[11]	0.0045(N^{-1})	70
[17]	0.002 (kPa^{-1})	~100
This Work	0.006(N^{-1})	200

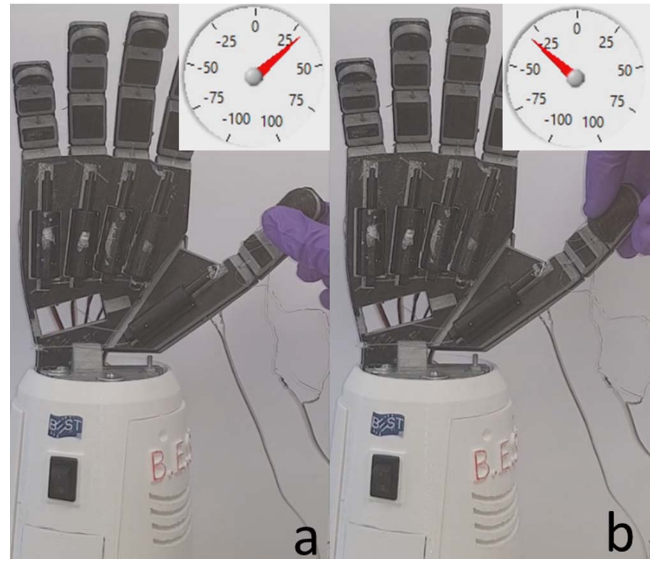

Fig. 5. Robotic end effector with soft embedded pressure distribution sensors and the response of the system presented by a custom made LabVIEW program. a) force applied on the right side of the finger-tip. b) force applied on the left side of the finger-tip and the response.

B. Demostration

Once the entire system was assembled a custom-made LabVIEW program was developed to present the data captured from the sensors. Fig. 5 presents the fully functional system and the response captured and presented in a custom-made LabVIEW program. In Fig. 5a the right side of the fingertip was gently pressured and on the top right side of the figure a gauge type indicator shows the additional percentage capacitance of the right sensor over the left sensor. Fig. 5b presents the fingertip pressed on the left side and the response of the system. The positive value represents the extra percentage capacitance of the right sensor over the left, while the negative value represents the extra percentage capacitance the left sensor over the right one.

IV. Conclusion

In this paper, a novel 3D printed soft fingertip with embedded tactile sensors is presented for touch feedback in robotics/prosthesis applications. The fabrication process and the electronics designed for embedded touch sensors is presented with demonstration of the system. As next step, the readout electronics will also be embedded in the fingertip to demonstrate embedding of full systems inside 3D printed hand. In this way, the human-like finger will be developed with distributed sensors and electronics embedded in the body and not wrapped around the curved surfaces as is done today.

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