3D-Printed Perceptive Robotic End-Effectors with Embedded Multimodal Sensors

Radu Chirila[1,2*], Abhishek Singh Dahiya[4], Oliver Ozioko[3], Philippe G. Schyns[2] and Ravinder Dahiya[4**]

[1] *James Watt School of Engineering, University of Glasgow, G12 8QQ Glasgow, U.K*

[2] *Centre for Cognitive Neuroimaging, School of Psychology and Neuroscience, University of Glasgow, G12 8QQ Glasgow, U.K*

[3] *Department of Electrical & Electronic Engineering, University of Derby, UK*

[4] *Bendable Electronics and Sustainable Technologies Group, Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115 USA*

** Graduate Student Member, IEEE*

*** Fellow, IEEE*

Abstract— Robust perception is crucial for autonomous and intelligent robots, and this can be achieved through a network of multimodal sensors embedded in the robotic body, like biological organs. Herein, we report a perceptive robotic end-effector, developed using multi-material additive manufacturing, for manipulation of delicate objects. The 3D-printed phalanges of the end-effector incorporate distributed resistive sensors to provide the multimodal touch and bend sensing capabilities. Each resistive sensor unit comprises a carbon black-Thermoplastic Polyurethane (TPU)-based conductive composite, along with a specially designed sensor frame for embedding purposes to ensure robustness. These embedded sensors show sensitivity of ~0.16% N^{-1} to compressive pressure and 0.06% per degree of bending angle for applied strain. Furthermore, they exhibit temperature sensitivity, registering approximately 1.6% change in response to a temperature shift from room temperature (25°C) to 45°C (hot perception), and approximately 1.3% for a change from 25°C to 5°C (cold perception). Finally, the 3D printed end-effector is used to grasp daily objects such as a soft ball and a paper cup to demonstrate its practical applicability towards the development of artificial limbs and human-friendly soft robots.

Index Terms—3D printing, additive manufacturing, end-effectors, embedded sensing, soft robotics.

I. INTRODUCTION

Sensation and perception are crucial for autonomous and intelligent robots to manipulate and explore delicate objects [1], safely interact [2], and adapt to unpredictable environments etc. [3-6]. They help robots take necessary action for localization (estimation of the self) and navigation through closed-loop control. Advanced tactile sensing technologies, historically rooted in rigid materials and grounded in precise theoretical models, have facilitated perception in traditional rigid robots. This achievement has empowered these robotic systems to excel in tasks requiring high precision, accuracy, and speed, particularly in object manipulation scenarios. As the integration of service robots into domestic, commercial, and industrial environments becomes increasingly commonplace, there arises a need to enhance the physical interaction between humans and robots to ensure safety. However, the use of rigid materials possesses safety concerns for human-robot collaboration and for manipulating soft objects for applications such as artificial enhanced (AI)-enhanced automatic sorting, assembly line management, and intelligent manufacturing for Industry 4.0.

To overcome these safety limitations, and to bring robots and humans together as task partners, in the last decade, the soft and compliant robotics field has garnered attention [2, 3, 7-9]. Soft robots are constructed from highly ‘soft’ and ‘compliant’ materials which endow novel features in them including higher degrees of freedom, adaptability to confined environments etc. Because of these features they could be used for manipulating delicate objects, providing safer human–robot interaction and so on. Tactile perception remains a critical frontier in the development of collaborative robots, representing a technology gap that demands attention and integration for future robotic systems [10]. Given the curved surfaces inherent in robotic components, the implementation of tactile sensors onto both the robot body necessitates the utilization of flexible and bendable robotic "skins"[11]. Research in this domain revolves around various aspects including material selection, optimized fabrication processes, sensor modalities, packaging methodologies, and associated electronic designs tailored for analyzing sensory feedback. Mechanical sensors such as strain and pressure are critical to execute the above-mentioned applications as they provide compliant robots with an ability to recognize the stimuli from both inside (i.e., proprioception) and outside (i.e., exteroception) [3, 6, 8, 12-16]. Implementing these abilities using single sensor strategies is interesting as it avoids integrating multiple sensors on a single substrate, which leads to complex circuit layout and manufacturing difficulties [17]. However, it is challenging to manufacture reliable, robust multimodal soft sensors because of the high dimensionality of compliant materials which brings uncertainty while predicting the sensing response under various mechanical loading.

Different sensing technologies such as flexible large area electronic skin (e-skin), smart E-textiles etc. have been explored to endow perception in soft robotic structures. Most of these devices are usually placed on the external surface of the robot’s body which often fails while executing an intricate task. One of the foremost challenges

Corresponding author: Ravinder Dahiya (r.dahiya@northeastern.edu).

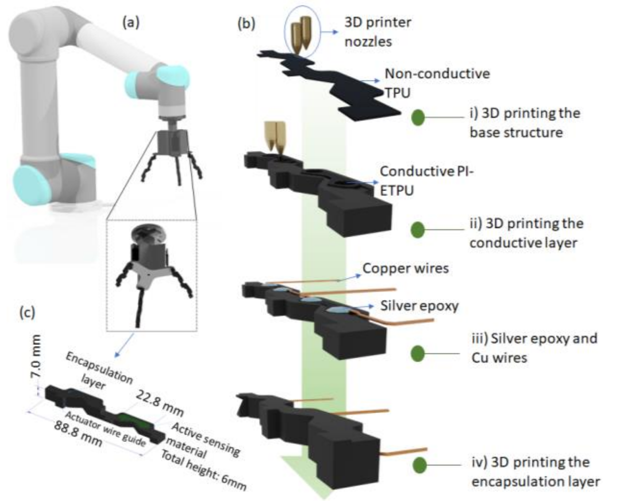

Fig. 1. Schematic illustration of the fabrication process to develop and test a perceptive robotic end-effector for manipulation of delicate objects. (a) robotic end-effector with the smart sensing phalanges having a distributed network of soft resistive touch and bend sensors. b) Fabrication steps for the 3D printed phalanges, and (c) single phalange showing the sensing element, sensing frame and actuator wire guide.

confronting robotics lies in achieving multimodal sensing capabilities, which denote a soft robot's ability to discern multiple physical parameters simultaneously. Present techniques often struggle to accommodate the elastic deformations characteristic of soft robots, namely stretching and bending, phenomena prevalent in applications such as wearables and smart textiles. Embedded sensing through the adoption of multi-material 3D printing offers potential to develop robust and stable soft sensing structures for strain, stress, and contact estimation [18, 19]. Multi-material 3D printing offers advantages over conventional manufacturing including resource-efficiency, digital (mask-less) fabrication, low-cost and potential of architecting electronic and multifunctional materials in a single run [18, 20-23]. Integration of a connected network of fully embedded touch and bend sensors into soft robotic structures is ideal for soft robotics applications. Soft robotic structures with such configurations could offer characteristic features such as directional sensing, strain distribution mapping etc. needed to develop intelligent end-effectors that can adapt to objects' shapes and dimensions.

In this study, we present a compliant gripper with cohesive network of distributed and embedded resistive sensors fully fabricated via multi-material 3D printing (Fig. 1). The integrated sensor network forms part of an adaptive end-effector capable of monitoring both internal motion (proprioception) and external mechanical stimuli (exteroception). These resistive elements undergo rigorous testing under bending and pressure conditions for assessment and refinement of the sensing performance, considering their inherent behavioural nonlinearities such as hysteresis and creep. The phalange is designed in a way that when it bends, because it is driven by a guided wire pulled by a servomotor, the motion is primarily defined by the areas with the weakest mechanical resistance. As such, the device will bend primarily from the two regions with active sensing layers. These active sensing regions are carefully positioned inside phalange to have different behaviours in response to pressure, and strain which is important leverage the data produced by the sensors and provide more information about the payload being picked up by the gripper, using less hardware.

II. MATERIALS AND METHODS

A. Materials

The resistive sensors were 3D printed using an Ultimaker S5 FDM 3D printer with 2 nozzles (AA 0.4 for the non-conductive NinjaTek NinjaFlex TPU filament and CC0.6 for the Palmiga PI-ETPU carbon black conductive TPU) enabling multi-material printing. During the sensor fabrication, the layer height was set at 0.1 mm for both materials. The conductive PI-ETPU filament was printed at a nozzle temperature of 245°C and the TPU was printed at a temperature of 210°C. The frame as shown in Fig. 1 is ~50.4mm overall length and ~5.15mm thickness was printed using the NinjaTek NinjaFlex TPU flexible filament and the sensing layer was fabricated using the Carbon Black PI-ETPU filament (~22.8mm long and ~2mm thick). In this layer-by-layer additive process, the devices were all 3D printed using the Ultimaker S5 3D printer. Since this printer is capable of multi-material printing, the sensing layer was seamlessly integrated into the gripper or end-effector during printing.

B. Sensing electrical characterization

The fabricated sensors were electrically characterized, and their results compared for repeatability. The sensors were separately attached to a bending setup which is controlled using a linear stage. This stage contains two linear motors having a resolution of ~0.1mm. The sensor electrodes were then connected to a Keysight TrueVolt 34465A digital multimeter) which is connected to a PC running a custom-made LabVIEW 2018 Robotics v18.0f2 program (National Instruments, Texas, USA) to measure the resistance of each sensor and to control the linear stage. The sensors were subjected to different bending angles in the range of ~10° to 30° by systematically moving the linear stage (~1mm step and ~10s delay between each bending angle) using the LabVIEW program. The output of the sensor was then logged using the digital multimeter.

C. Application as end-effectors

The fabricated end-effector was attached to a Universal Robotics UR5 robotic arm to demonstrate its gripping capabilities. Sensor readout and control of the robotic end-effector was done via an STM32 Nucleo H7A3ZI-Q microcontroller communicating through USB to a data-logging computer. Its functionality was tested by repeatedly grabbing, lifting, and unloading different soft objects such as a coffee cup and a ball.

III. RESULTS AND DISCUSSIONS

A. Fabrication of 3D printed embedded resistive sensors

Fig. 1 schematically shows the multi-material 3D printing approach to obtain embedded, distributed strain and pressure sensing phalanges for adaptive robotic end-effectors applications. As exemplified in Fig. 1b, the fabrication process comprised four sequential steps. Initially, a non-conductive TPU encapsulation base layer was printed (Fig. 1b

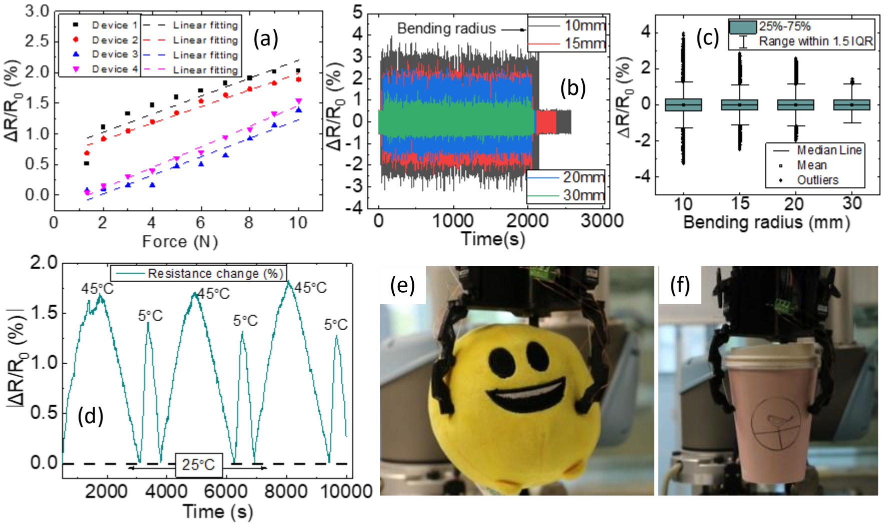

Fig. 2. (a) The change in the relative resistance of the four printed sensors with increase in compressive forces, (b) sensor response with applied bending radius, (c) box and whisker plot for the data shown in Fig. 2b, and (d) heating–cooling cycle to monitor resistance variation between 5 to 45 °C, (e-f) grasping capabilities of the fabricated end-effector for grasping (e) a soft ball, and (f) a paper cup.

(i)). Subsequently, the functionalized (conductive) PI-ETPU sensing layer was printed concurrently with the non-conductive TPU encapsulation. To facilitate the attachment of wires to the sensing layer, the printing process was halted at the midpoint of the device's total height. Wires were affixed using silver epoxy. It is worth noting that the silver epoxy was fully cured before recommencing the printing process.

B. Electrical characterization of embedded resistive sensors

To evaluate the repeatability and reliability of the fabrication process, electrical performance of 4 resistive sensors, fabricated under similar conditions, was carried out. Fig. 2a shows the relative change of resistance of each sensor fabricated with respect to increasing compressive force, applied from 2N to 10N. It is clear from the figure that all sensors show a linear increase in sensor response with an increase in applied force. The linear fitting of the obtained experimental data shows sensitivity of approximately 0.16% N^{-1} to compressive pressure. Sample to sample variation in response (%) is noticeable from Fig. 2a. There could be many possible reasons for such variations. For instance, non-uniform thickness of printed layers and inhomogeneity of the filler particle distribution could lead to such variations. Nevertheless, small device variations such as in our case, could be managed using appropriate conditioning circuits.

Next, the sensors were bent at different radii of curvature while their resistance was monitored. The bending was performed using a Yuasa endurance testing system. The bending radius varied from 30mm to 10mm. The results of the cyclic bending tests of the sensors over a range of bending radius are presented in Fig. 2b. The change in resistance of the sensors with bending is presented over time. An increase in the sensor response was observed with a decrease in the applied bending radius from 30mm to 10mm i.e., with an increase in applied strain. For correct understanding of the displayed data in Fig. 2b, a box and whisker plot are shown in Fig. 2c. It is a convenient way of visually displaying the data distribution through their quartiles. The lines extending parallel from the boxes are known as the “whiskers”, which are used to indicate variability outside the upper and lower quartiles. Outliers are plotted as individual dots that are in-line with whiskers. In our case, the sensors show outliers of 4% change in resistance for 10mm bending radius and ~1.5% under 30mm bending radius. The resistance percentage change is in negative as these composite materials are prone to creep, hysteresis and non-linear response [24], partly resulting from the conductive composite materials and the sensors are calibrated around their initial values. Table I shows the performance comparison of the fabricated 3D printed devices as a pressure/bend sensor with the reported sensors.

Next, the change in resistance (%) with time was monitored with change in temperature. A continuous cycle was performed to obtain the data needed to evaluate thermal sensitivity. For this, the temperature was changed from 25 to 45 °C then ramped to 25 °C and then decreased to 5°C. The data exhibits temperature sensitivity, registering approximately 1.6% change in response to a temperature shift from room temperature (25°C) to 45°C (hot perception), and approximately 1.3% for a change from 25°C to 5°C (cold perception).

C. Applications

Proprioceptive sensation via embedded resistive sensors is essential for soft robotic grippers to realize safe and dexterous grasping. For this, distributed sensors (#2) are fabricated for each phalange, placed one at the tip (for pressure sensing, performing exteroception) and one at the middle (for strain sensing, performing proprioception). In total 3 phalanges were fabricated and integrated together to a Universal Robotics UR5 robotic arm to demonstrate its gripping capabilities for soft objects including a soft ball and a paper cup (Fig. 2e-f). Due to the adoption of soft sensing technology, the fabricated gripper showed good inherent mechanical compliance to adapt itself to the grasped objects’ profiles without failure.

Additionally, the sensor output can be leveraged to infer additional pieces of information about the object being grasped, such as weight of payload and relative hardness, or motion information in relation to end-effector kinematics (i.e., acceleration). In real life applications, the gradient of resistive change differs between phenomena observed (bend, pressure, temperature). By using signal conditioning algorithms alongside machine learning, we will be able to discern between pressure, strain, and temperature. As an example, when the end-effector grasps an object, we can sense the bending (proprioception). On the other hand, when the object is lifted, it acts on the phalanges of the gripper (which are grasping the object). This creates a shift in behavior, signaling a shift in dominant effects, from strain to pressure. We are currently working on using the robotic end-effector to infer the weight of payload during manipulation using machine learning algorithms.

TABLE I: Comparison of the 3D printed devices performance as a pressure/bend sensor with other reported 3D printed sensors.

Composition	**Bending angle or radius**	**Sensitivity ($\Delta R/R$ (%))**	**Ref.**
TPU-MWCNT	30°	2.5	[25]
TPU – CNT/Ag NP	30°	5	[26]
TPU-MWCNT/PCA	45°	8.5	[27]
Ecoflex/graphite	NA	0.3% kPa^{-1}	[18]
Graphite paste	NA	0.346 kPa^{-1}	[28]
This work	10mm	Strain – 3.5	This work
		Pressure - 0.16% N^{-1}	

IV. CONCLUSION

In this work, a multi-material 3D printing approach was used to fabricate phalanges. These phalanges were carefully designed to have a connected network of embedded and distributed soft resistive sensors for obtaining smart and adaptive soft robotic structures with intrinsic multimodal sensing. The distributed sensors embedded inside the phalanges leverage the resistive property of a 3D printed conductive PI-ETPU which changes during bending and applied pressure. Four embedded resistive sensors were designed, fabricated, and characterized under similar conditions to understand the repeatability of the fabrication process and response from the sensors. The sensors exhibited a stable response with sensitivity of approximately 0.16% N^{-1} to compressive pressure, 0.06% per degree of bending angle for applied strain (measured between 10-30mm bending radius), and 1.6% change in response to a temperature shift from room temperature (25°C) to 45°C (hot perception), and approximately 1.3% for a change from 25°C to 5°C (cold perception).

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