Multidirectional strain sensor using multimaterial 3D printing

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***Abstract*— This paper presents a fully 3D printed multidirectional strain sensor for robotic applications. The all-printed sensor constitutes a piezoresistive sensing layer of flexible carbon black engineered thermoplastic polyurethane (PI-ETPU), and a structurally engineered sensor frame printed using rigid polylactic acid (PLA). The sensor is printed using multi-material 3D printing and systematically positioned in the frame to uniquely detect multidirectional mechanical loading. The stress and strain distributions on the developed sensor structure, as well as the piezoresistive coupling of the active sensing layer are investigated using COMSOL Multiphysics. The results show discrete resistive responses over the three different displacements simulated. The unique motion and the response give the individual sensors the ability to infer new pieces of data such as angle and orientation from the piezoresistive behavior of each sensor. This makes the sensors promising for a wide range of applications, from artificially intelligent robots to rehabilitation and 3D texture mapping.**

***Keywords*— strain sensing; 3D printing; multidirectional; COMSOL; piezoresistive; robotics**

I. Introduction

The rapid and underpinning advances in 3D printing technologies [1]–[4] has shown immense potential for the advancement of numerous applications such as robotics [5], [6], wearable systems [7], prosthetics [8]–[10], medical instruments [11], [12], and human-machine interfaces [13], [14]. This is owing to advantages such as cost-effectiveness, design flexibility, the ability to produce complex structures and smart functional devices in a resource efficient manner (additive manufacturing). New 3D printing techniques, such as multi-material printing [4], [15], [16], enable the integration of new functionalities such as sensing and actuation as part of mechanical structures [4], [15], [16]. This is increasingly utilized in the realization of robots with seamlessly integrated advanced sensing capabilities. In fact, a number of sensors based on mechanisms such as resistive [17], capacitive [18], piezoelectric, triboelectric etc. [19] have been integrated into robotic hands employing different 3D printing techniques [4]. In all, the goal is often to print sensing layers as part of the mechanical structure. For instance, instead of separately integrating sensors on a robotic hand, researchers have explored the printing of smart materials such as 3D printable conducting thermoplastic polyurethane (TPUs), carbon black, carbon nanotubes (CNT) or their functionalized versions [2], [3].

In this work, we have utilized a carbon black PI-ETPU filament to fabricate a fully 3D printed piezoresistive multidirectional strain sensor. This sensor enables simultaneous measurements of strain applied at different angles which makes it possible to accurately determine the relative motion between the sensing layer and the sensor's frame. This design aims to demonstrate that an array of different motions and gestures can be accurately detected, thus helping reduce the sensor redundancy in intelligent robotic applications and increasing the variety of information collected. To achieve this, we first designed and simulated the sensor using COMSOL Multiphysics to understand areas of maximum stress and strain, the piezoresistive behavior and its change with direction and force. Following this, we fabricated two of these sensors using multi-material 3D printing techniques which enabled the sensing material and the sensor frame to be printed in one go using fused deposition modelling (FDM). The design of multidirectional strain sensor and 3D printed device are shown in Fig. 1.

This paper is organized as follows: Section II describes the experimental arrangement for the presented sensor design. Section III describes the results of the simulation and the characterisation of a printed sensing unit of the sensor. Finally, the key outcomes of this study are summarized in Section IV.

II. Experimental section

A. Sensor design

The directional strain sensor leverages capabilities of the multi-material 3D printing technologies and has two main

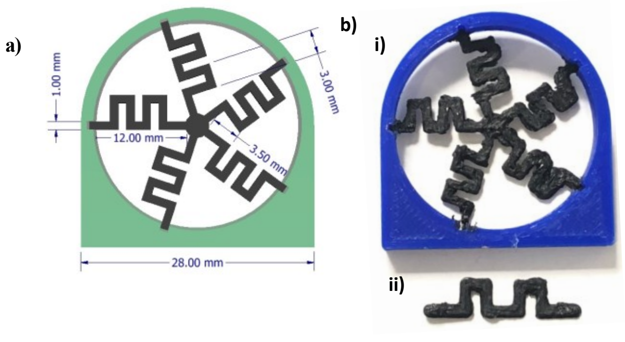

Fig. 1. a) Sensor 3D model with dimensions (top view), and b) i) fabricated sensor, and ii) individual PI-ETPU sensing unit.

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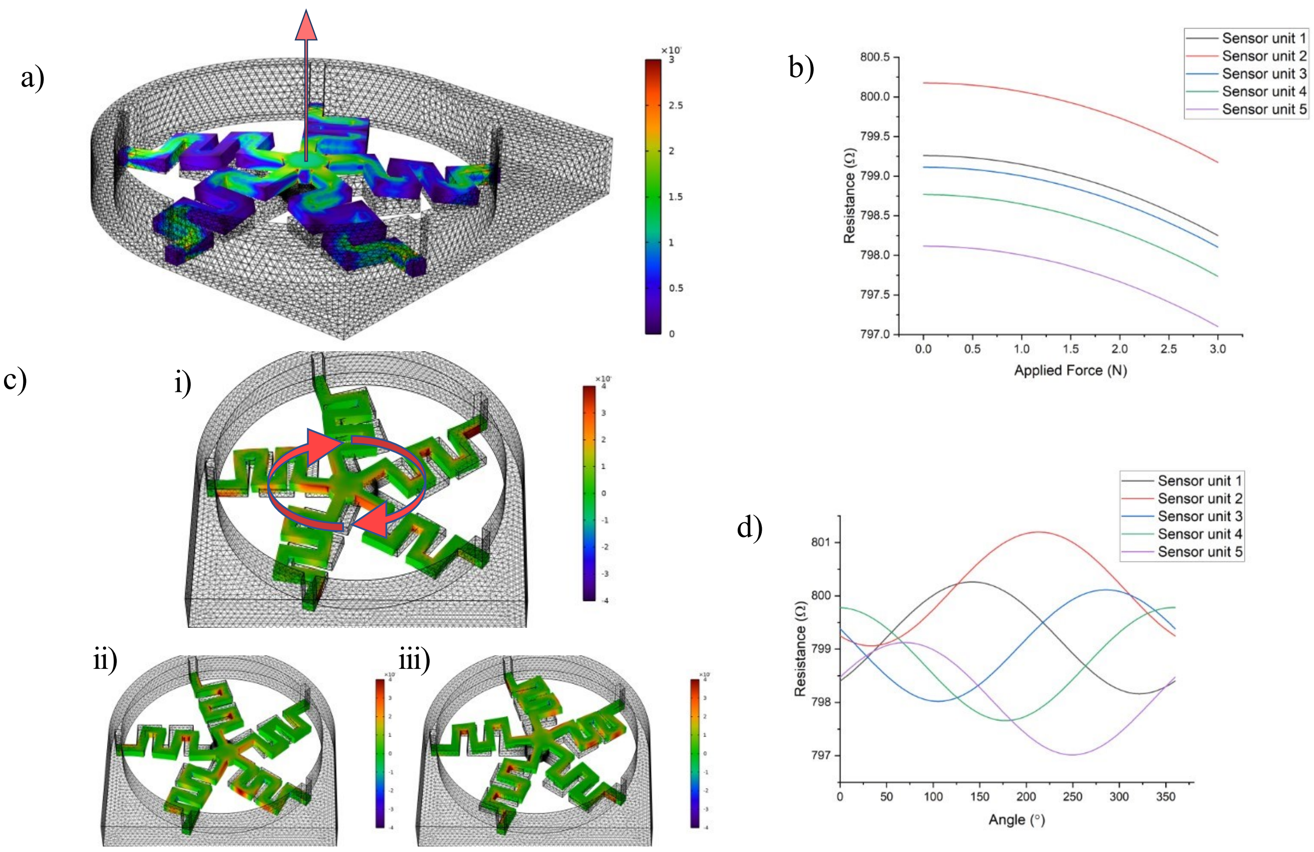

Fig. 2. a) First principal stress on the sensing layer (with displacement), b) Piezoresistive response of the 5 sensing units, c) i) - iii) First principal stress on the sensing layer during planar motion (with displacement), in different positions and d) Piezoresistive response of the 5 sensing units during planar motion.

components; 1) the active sensing region which comprises five coplanar piezoresistive sensors made from flexible carbon black PI-ETPU and structurally laid out in a star shape with a common ground (Fig. 1); and 2) a structurally fingertip-shaped rigid sensor frame which was 3D printed using non-flexible polylactic acid (PLA) filament. The frame was chosen specifically to act as a mechanical support, and a static reference point, thus enabling the measurement of the relative movement of the central element of the active sensing layer. When the sensing region moves, the high compressive stress in the integrated PI-ETPU sensing units causes the carbon particles in the conducting matrix to come closer, thus triggering a decrease in resistance. In the same time, the opposite sensing units stretch, in turn causing an increase in resistance, even under relatively small displacement conditions. The directional strain sensor was first designed as shown in Fig. 1, using Autodesk Inventor Professional 2022, a Computer-Aided Design (CAD) software. The designed CAD model was then imported into COMSOL Multiphysics where it was simulated and validated to enhance the core functionalities of the device.

B. *Model Definition*

In the simulation software, we defined the materials of the system as depicted in Table 1, and carried out a Multiphysics simulation, coupling a stress simulation and an electrical simulation to investigate the piezoresistive behavior of the sensor and observe the maximum stress and strain regions in order to optimize the shape and positioning of the sensing units within the active sensing layer. Each sensing unit was defined electrically as a pair of terminals, with a potential difference of 5V between them. The electrical resistivity of the carbon black PI-ETPU was set at 3.8 kΩ-cm (obtained experimentally), and the relative permittivity, $\varepsilon_{\text{isometric}} = 5$ (constant) [20]. The piezoresistive behavior was modelled after the lightly doped polycrystalline n-Silicon, but the piezoresistive coupling matrix was set as a diagonally symmetric stress array, to present the same behavior regardless of the direction of the stress acting upon the material.

C. *Multiphysics Simulation*

To gain valuable insight into the array of applications possible with this design, 3 separate classes of motions were simulated: pressing (Fig. 2a), planar rotation of the common terminal (Fig. 2c), and 3 directional rotations of the common terminal (Fig. 3a). Following this, the simulations were run using a segregated solver (for solid mechanics and electrical currents) and a direct solver (PARDISO) with iterative precision refinement over 100 iterations, and a relative error tolerance of 10^{-4}. The force applied to the sensor was simulated as a parametric sweep in the range of (0 – 3 N). The stress and the piezoresistive behavior of the sensor were then analyzed.

D. *Sensor Fabrication*

According with the simulations results, the sensor was 3D printed using a Ultimaker S5 printer, with a 0.6 mm nozzle for the PI-ETPU (Palmiga 95-250 Carbon Black PI-ETPU) filament and a 0.4 mm nozzle for the PLA (RS-PRO) material (Fig. 1b (i)). During the sensor fabrication, the layer height was set at 0.1 mm for both materials. The conductive PI-

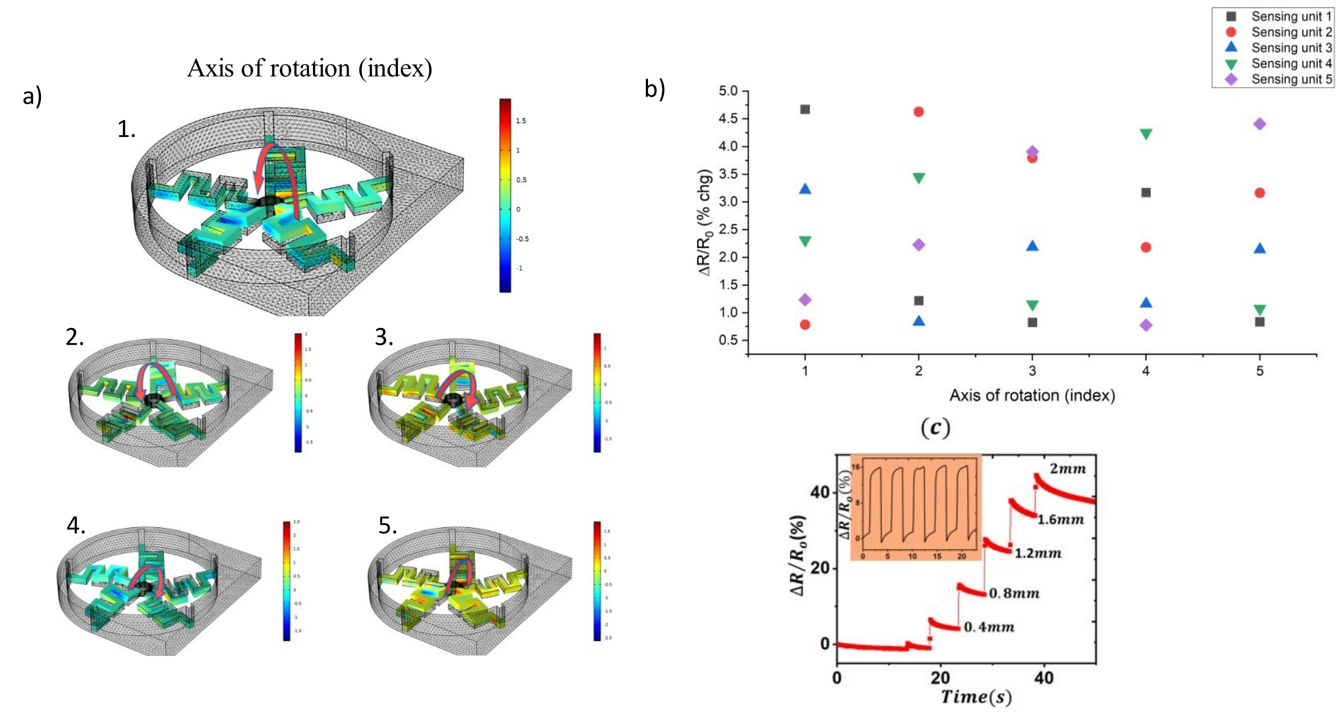

Fig. 3 a) 1-5 Volumetric change in resistance during 3d rotation (with displacement), b) Percent change of resistance for each of the 3D rotation test cases and (c) Response of a single fabricated sensor showing the change in resistance and stability. The inset shows the stable cyclic response form the sensing unit.

ETPU was printed with a nozzle temperature of 245°C, while the PLA was printed with a nozzle temperature of 210°C. To understand how a single sensor will practically respond, we printed a sensing unit individually (Fig. 1b. (ii)) and characterized it under different stretching conditions. During the electrical characterizations, a stepwise stretching from 0.4 mm to 2 mm, in steps of 0.4 mm, was carried out. Also, cyclic loading and unloading was carried out to understand the stability of the 3D printed sensor. The stretching was carried out using a custom-made stretching tool controlled by a computer-controlled linear motor with a resolution of ~0.1 mm [21].

III. Results and Discussions

A. Vertical press

Fig. 2a shows the vertical press simulation results. Here, the center of the active sensing layer is placed in the middle of the sensor, equidistant from the rigid frame, and the force applied is only vertical. The sensing units move in the same direction simultaneously. Hence, the response of the sensing units will vary by the same amount, at the same time (Fig. 2b).

B. Planar movement

Fig. 2c shows the planar rotation simulation results. In this situation, the force applied on the common terminal of the sensing units is planar and constant at 3N. The change in resistance with varying angle is shown in Fig. 2d. This case proves the piezoresistive behaviour of the sensing units and provides discrete sets of values for each angle. Hence, the movement direction as well as the relative angle of planar force can be inferred from the response of the 5 sensing units.

C. 3D rotations

Fig. 3a shows the 3D rotation simulation results. In this test case, 5 different spatial rotations were investigated. Each rotation is described by an index and the response of the sensing units for each of the mentioned rotations was recorded (Fig. 3b). The simulation shows the resistance of each sensing unit as a percent change from the baseline resistance. Thus, the relative axis of rotation can be inferred from the same piezoresistive response.

D. Printed sensing unit characterization

Under stretching, the fabricated sensing unit shows discrete $\Delta R/R_0$ variation levels, with a maximum of 40% (Fig. 3c). Additionally, the fabricated sensor unit shows a stable cyclic response to stretching (inset Fig. 3c).

Table 1. Mechanical properties of the materials used in the COMSOL simulation

Material Property	PLA [22]	Conductive PI-ETPU [23]
Density [g/cm^3]	1.25	1.3
Young's modulus [MPa]	4107	15
Poisson's ratio	0.35	0.45

IV. Conclusions

This paper presents a simulation study of a fully 3D-printable multidirectional strain sensor. The structure of the sensor leverages the piezoresistive property of a 3D printed conductive PI-ETPU which varies under stress. The stress and strain distribution on the sensing layer were investigated using COMSOL Multiphysics and the results show that the 5 individual sensing units can respond differently to the 3 test-cases simulated in this paper. This highlights a different approach to provide sensorisation to robots and provides proof that a single sensing layer can generate discrete datasets for wide range of movements. At the same time, the simulation results show the viability of the designed strain sensor and its utility for robotic applications based on robust data inference from discrete responses. In all, this sensor design shows promising behaviour for applications such as texture mapping and slip detection in robotic prosthetic hands.

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