Multi-material 3D Printed Bendable Smart Sensing Structures

Habib Nassar, Markellos Ntagios, William Taube Navaraj, Ravinder Dahiya
Bendable Electronics and Sensing Technologies (BEST) Group, University of Glasgow, G12 8QQ, United Kingdom
Correspondence to: Ravinder.dahiya@glasgow.ac.uk

Abstract— This paper presents a novel additive manufacturing method to obtain bendable smart sensing structures having printed strain sensors and interconnects to gain access to embedded electronic components. The presented smart structure is obtained by simultaneous printing of functional materials along with conventional polymer-based 3D printing materials. To this end, a low-cost open-source 3D printer was augmented with a silver palladium metallic paste extruder. The strain sensors in the presented 3D printed smart structure are particularly useful for wearable motion sensing applications such as knee joint motion analysis. The printed interconnects allow for electrical connection with the Light Emitting Diodes (LEDs) embedded within the 3D printed structure. With electronic components embedded in the flexible 3D printed structure, this work also demonstrates a novel method for soft packaging of electronic and sensing components. The electrical tests conducted on the smart structure show excellent electrical continuity. The 3D printed strain sensors, tested in static and dynamic bending conditions, showed a linear response of resistance. Under no strain, the resistance of the sensor was measured to be 0.9671 Ω (resistivity of 9.671×10^{-6} Ω.m) and during testing it exhibited a gauge factor of 1. Multi-material additive manufacturing demonstrated in this paper opens a new direction for fabrication of complex 3D structures with embedded sensors and electronics and offers significant advantages for rapid prototyping and packaging.

Keywords — 3D printing, Embedded sensing, Strain sensor, Wearables, Soft Robotics

I. Introduction

Electronic components and sensors are traditionally assembled on one or both sides of 2-dimensional PCBs before packaging. However, this does not fully utilise the 3-dimensional space available in the package. In this regard, creating complex 3D electronic systems and circuits, which cannot be produced in any other way available today, can open new avenues for packaging and manufacturing, especially for flexible and wearable systems [1, 2]. 3D assembly of electronics and sensors can also help achieve compact integrated smart sensing structures with 3D circuitry. This, in turn, will further boost the electronics manufacturing industry, which has brought significant gains in emerging fields such as robotic automation, flexible electronics [3], Artificial Intelligence (AI) and Industry 4.0. It is widely understood that 3D printing, or additive manufacturing (AM), has the potential to become a technology that will impact our lives for the better [4]. In fact, it is already revolutionising the 3D prototyping sector as the layer-by-layer addition of material allows for design flexibility, prompt design changes and mass customisation previously unavailable using traditional manufacturing processes [5]. As a result, 3D printers are available today to print either metal, polymers, conductive polymer composites, ionically conductive fluids or biological materials [6–15]. However, simultaneous printing of multiple functional materials such as metals and structural materials such as polymers, to realise printed sensors and fully packaged electronic systems, has not been attempted. This paper presents interesting results in this direction with multi-material 3D printing to develop printed conductive tracks in a 3D printed sensing structure. Silver-palladium conductive tracks embedded in the 3D printed structure have been realized to: (a) connect off-the-shelf components which are also embedded in the 3D printed structure, and (b) to act as the strain sensors. The 3D printed conductive paste has much higher conductivity (resistance of the device under no load is just 0.97 Ω) than existing solid conductive filaments such as conductive polylactic acid (PLA) which has a perpendicular volume resistivity of 30 Ω-cm. The custom setup developed for multi-material 3D printing can be used to print various functional materials with varying physical properties.

This paper is organised as follows: The design of a desktop 3D printer, adapted to include a conductive paste extrusion mechanism, and the traditional polymer extrusion materials are presented in Section II. The design of the printed wearable structure, consisting of a strain sensor and printed conductive tracks connected to fully embedded LEDs and the interfacing circuits, is explained in Section III. The experimental results showing the working of the 3D printed structure are also discussed in Section III and the key results are summarized in Section IV along with the future outlook of this work.

II. 3D Printer Design & Materials

A. 3D Printer Customization

The difficulty of dynamically altering the setup of light-based printing methods (such as stereolithography or laser sintering) currently makes them unsuited for multi-material 3D printing. However, ink/paste-based printing methods (such as direct ink write (DIW)) can be adapted with readily available desktop 3D printers. For this reason, a modified version of the Bowden Large Volume Extruder (LVE) [16] is used here. The LVE was integrated with a RepRap Pro Ormerod 2 desktop 3D printer to incorporate a second printing head extruding inks and pastes (Fig. 1a). This platform was chosen because it is opensource, meaning it is readily available and customisable. An adjustable and easily replaceable attachment, housing the nozzle printing head was designed specifically to fit on the Ormerod 2 x-carriage (Fig. 1b). The LVE adopted in this work overcomes some of the issues faced by paste extruders, which include requiring bulky air pressure supply units and operating

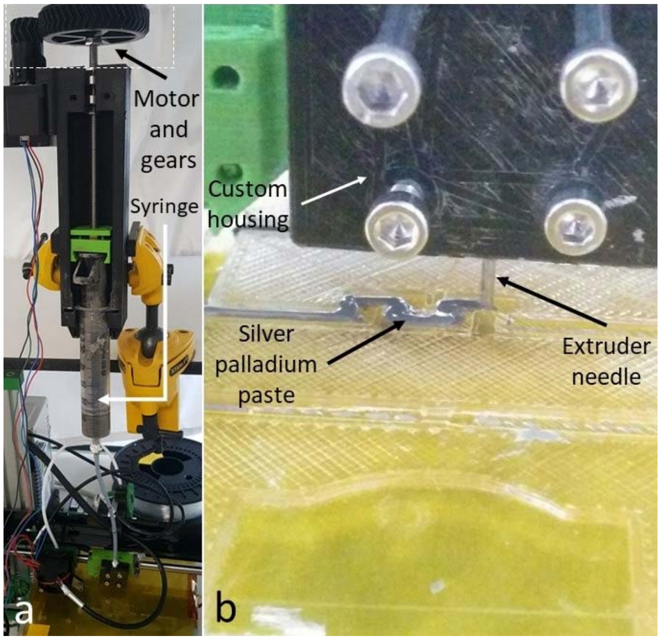

Fig. 1: Modified 3D printing set up. (a) Conductive paste extrusion system. (b) Syringe and custom housing for the extrusion mechanism.

without retraction [16]. Without the ability to retract, traditional extruders are susceptible to material leakage which can cause artefacts and deteriorate the print quality. Placement of the syringe setup directly on top of the moving x-carriage is avoided as it increases unwanted vibrations in the system and decreases the print speed because of the added mass [17].

The additional NEMA 17 stepper motor used with LVE is driven by the DUET Ethernet control board which supports dual extrusion. The motor drives the gear system which in turn, controls the forward flow or retraction of the conductive paste from the Luer lock syringe. The syringe is first connected through a wide Bowden tube (1/4-inch inner diameter) to a Luer lock connector which, in turn, connects to a narrow (1/16-inch inner diameter) tube. The wider tube at the start helps prevent blockage and allows for smooth flow of the paste. The narrow tube is then connected by another connector to an 18 Gauge blunt needle (0.84mm diameter) which is fixed onto the printer's x-carriage. The offset distance between the two nozzle heads is 70mm which is declared in the board's firmware.

B. Materials and Methods

The flow behaviour of the inks' droplets can be characterised by the ink's viscosity, surface tension, shear yield stress, and shear elastic and loss moduli. The following equation is used to relate inertial and surface tension forces to viscous forces:

$$Z = \frac{1}{Oh} = \frac{Re}{\sqrt{We}} = \frac{\sqrt{\rho\gamma L}}{\mu} \qquad (1)$$

where Z is the reciprocal of the Ohnesorge number (Oh), which is a dimensionless parameter with value between 1-10 for ideal droplet formation [15]. Re is the Reynold number, We is Weber number, ρ is density, γ is surface tension, μ is viscosity, L is the characteristic droplet length (usually equal to droplet diameter). Droplet velocity should be at least equal to:

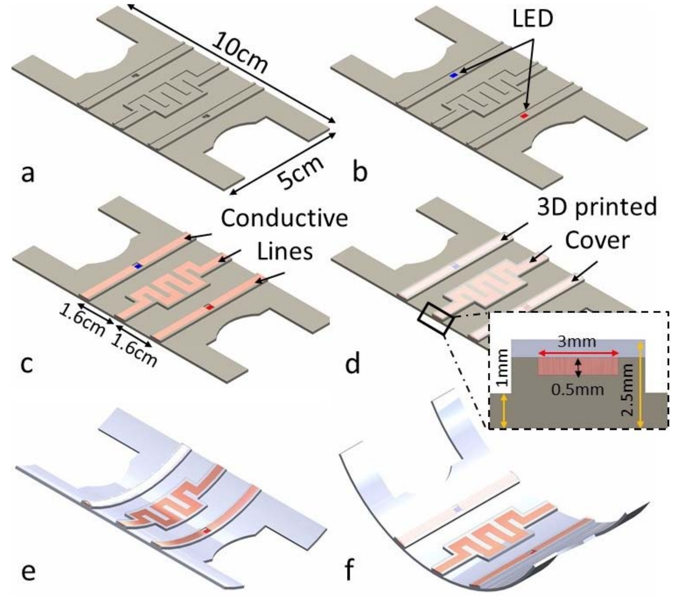

Fig. 2: CAD design of the printed structure. (a) The bottom layer with empty cavities. (b) Placement of the coloured LEDs. (c) Silver-palladium paste printed. (d) Structure with the top plastic layer printed embedding the sensor and electronics. (e) Y-axis bending. (f) X-axis bending

$$v = \sqrt{4\gamma/\rho d} \qquad (2)$$

where d is the nozzle diameter, v is the ejected droplet velocity. In our setup, the nozzle diameter is 0.84 mm and so the feed-rate for the paste extruder is set to 0.5 mm/min.

A silver palladium paste (ESL 9694-SA) was used as the conductive material as it exhibits excellent adhesion, good solderability, and high conductivity for our application. Its viscosity was decreased by adding 20% ethanol, as a solvent, and mixing well for 20 minutes. The paste is dried after printing by the printer's heated bed at 120ºC for 15 minutes. This reduced the resistance across the sensor from ~6 MΩ (before heating) to ~1 Ω (after heating). This occurs because the solvent evaporates leaving the particles to come in contact with each other. Material comparisons for resistive strain sensors have shown liquid metals to be favourable to inks with conductive particle networks and ionic fluids in a number of ways [13, 18].

The substrate flexible material used in the 3D printing process is clear Glassbend Flexi material (RS Components). The Flexi material is identified as flexible and stretchable enough to allow for sufficient adaptation to human wearable applications and to follow reversible deformation. This transparent substrate allows the embedded LEDs to be seen glowing within the structure. The feed-rate for printing this material is 1800mm/min and the diameter of the nozzle it is extruded from is 0.5mm.

After the bottom plastic layer is printed, the LEDs are placed at their designated locations in the structure. Then the printing of conductive paste follows to connect LEDs and to realize the strain sensors. After that, another plastic layer is printed on top to provide the fully integrated package. These steps are conducted in one print with a pause initiated only to place the LEDs.

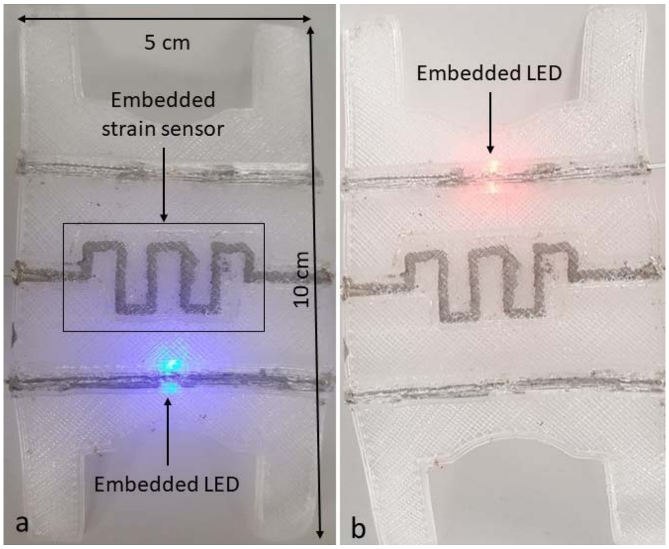

Fig. 3: (a) Fabricated Multi-material 3D Printed Smart Sensing Structures with the fully embedded blue LED. (b) Testing of the fully embedded red LED.

III. RESULTS AND DISCUSSION

For this work, a standard resistive strain sensor with a zig-zag shape (Fig. 2) was designed to demonstrate the printing capability of the setup. The printed sensor structure is 10 cm long, 5 cm wide and 2.5 mm thick (Fig. 2). The flexibility and light weight nature of the structure allow it to be strapped on the knee without discomforting the user. The printing direction was set to be along the length of conductive tracks to prevent crossovers. The planar dimensions of the structure were designed to be an integral multiple of the nozzles' diameters to prevent inconsistencies from the slicing software Slic3er. The vertical dimension is an integral multiple of the printing layer height (i.e. 0.1mm). To ensure reliable functionality, the width of conductive tracks is more than 3 times the diameter of the paste extruding nozzle, and the spacing between the tracks is at least 4 times the nozzle diameter (to ensure there is no short-circuiting due to potential extra material extrusion) [14]. Next to the strain sensor are two conductive tracks, designed to connect to SMD LEDs, which are fully embedded in the packaged structure. The tracks extend along the length of the structure, so they can be easily connected to external electronics.

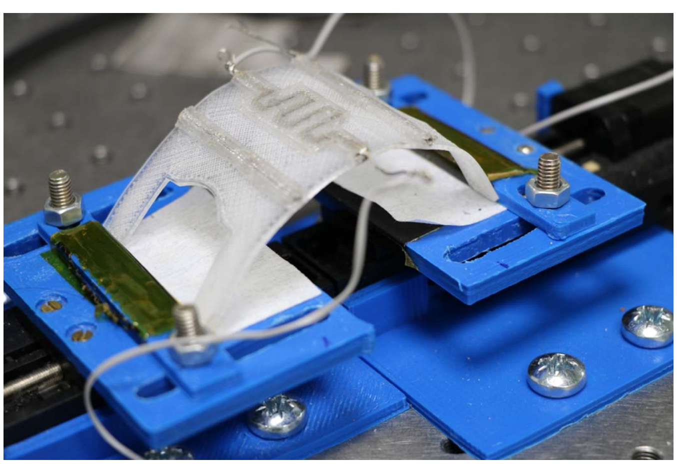

Fig. 4: Bending test set up to evaluate the embedded printed strain sensor.

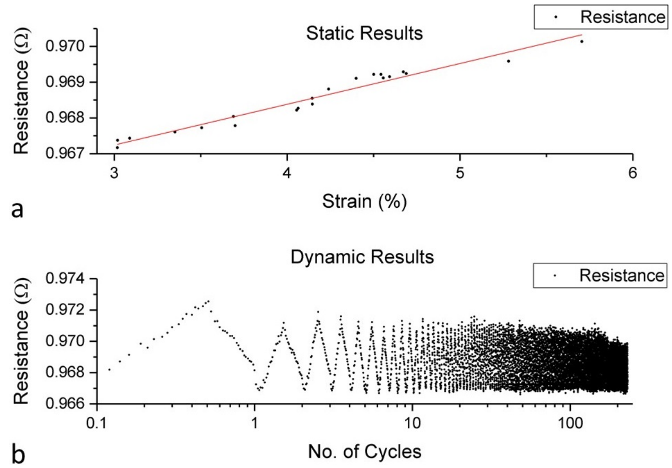

Fig. 5: (a) Static measurements of the change in resistance with respect to strain. (b) Dynamic testing of the strain sensor for 250 bending cycles.

Fig. 3 shows the glowing LEDs which are embedded in the prototype. The testing of the strain sensor was carried out to measure the change in resistance with bending. Dynamic and static testing of the strain sensor was done with a bending setup [19], shown in Fig. 4. The printed resistive strain sensor was connected to a Keysight digital multimeter (34461A) for measurements. The measured resistance of the device under no load was found to be 0.967 Ω. The sensor experiences a 6% increase in its resistance for a 6% bending strain (gauge factor of 1). Fig. 5a presents the results of the static measurements showing the observed linear trend between resistance and strain. Similarly, the dynamic behaviour of the device for 250 cycles is presented in Fig. 5b. The stable value of resistance demonstrates the feasibility of the presented advanced AM approach.

IV. CONCLUSION

With a one-step procedure for simultaneous printing of functional and structural materials, this paper demonstrates the feasibility of an advanced additive manufacturing process to realize complex packages with embedded sensing and electronic components. The smart sensing structure prototype developed using this process was tested and characterized under static and dynamic bending conditions. The presented advanced 3D AM approach has the potential to produce complex 3D structures with much lesser processing steps than the current state of the art methods to obtain fully embedded integrated sensors and circuits. Future work will involve some of these complex shapes realized with a wider range of functional materials.

ACKNOWLEDGEMENTS

This research is supported by Engineering and Physical Sciences Research Council (EPSRC) Fellowship for Growth - Printable Tactile Skin (EP/M002527/1).

REFERENCES

[1] W. Dang, V. Vinciguerra, L. Lorenzelli, and R. S. Dahiya, "Printable stretchable interconnects," *Flex. Print. Electron.*, vol. 2, no. 1, 2017.

[2] S. Gupta, W. T. Navaraj, L. Lorenzelli, and R. S. Dahiya, "Ultra-thin chips for high-performance flexible electronics," *npj Flex. Electron.*, vol. 2, no. 1, p. 8, Dec. 2018.

[3] S. Khan, L. Lorenzelli, and R. S. Dahiya, "Technologies for Printing Sensors and Electronics Over Large Flexible Substrates: A Review," *IEEE Sens. J.*, vol. 15, no. 6, 2015.

[4] U. Bhatia, "3D printing technology," *Int. J. Eng. Tech. Res.*, vol. 3, no. 2, pp. 327–330, 2015.

[5] A. J. Lopes, E. MacDonald, and R. B. Wicker, "Integrating stereolithography and direct print technologies for 3D structural electronics fabrication," *Rapid Prototyp. J.*, vol. 18, no. 2, pp. 129–143, Mar. 2012.

[6] S. J. Leigh, R. J. Bradley, C. P. Purssell, D. R. Billson, and D. A. Hutchins, "A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors," *PLoS One*, vol. 7, no. 11, p. e49365, Nov. 2012.

[7] E. MacDonald *et al.*, "3D printing for the rapid prototyping of structural electronics," *IEEE Access*, vol. 2, pp. 234–242, 2014.

[8] G. Postiglione, G. Natale, G. Griffini, M. Levi, and S. Turri, "Conductive 3D microstructures by direct 3D printing of polymer/carbon nanotube nanocomposites via liquid deposition modeling," *Compos. Part A Appl. Sci. Manuf.*, vol. 76, pp. 110–114, Sep. 2015.

[9] S. W. Kwok *et al.*, "Electrically conductive filament for 3D-printed circuits and sensors," *Appl. Mater. Today*, vol. 9, pp. 167–175, 2017.

[10] D. Espalin *et al.*, "3D Printing multifunctionality: structures with electronics," *Int J Adv Manuf Technol*, vol. 72, pp. 963–978, 2014.

[11] Z. Zhu *et al.*, "3D Printed Functional and Biological Materials on Moving Freeform Surfaces," *Adv. Mater.*, vol. 30, no. 23, p. 1707495, Jun. 2018.

[12] A. Frutiger *et al.*, "Capacitive soft strain sensors via multicore-shell fiber printing," *Adv. Mater.*, vol. 27, no. 15, pp. 2440–2446, 2015.

[13] M. T. Rahman, R. Moser, H. M. Zbib, C. V. Ramana, and R. Panat, "3D printed high performance strain sensors for high temperature applications," *J. Appl. Phys.*, vol. 123, no. 2, p. 024501, Jan. 2018.

[14] K. Elgeneidy, G. Neumann, M. Jackson, and N. Lohse, "Directly Printable Flexible Strain Sensors for Bending and Contact Feedback of Soft Actuators," *Front. Robot. AI*, vol. 5, p. 2, Feb. 2018.

[15] R. L. Truby and J. A. Lewis, "Printing soft matter in three dimensions," *Nature*, vol. 540, no. 7633, pp. 371–378, 2016.

[16] K. Pusch, T. J. Hinton, and A. W. Feinberg, "Large volume syringe pump extruder for desktop 3D printers," *HardwareX*, vol. 3, pp. 49–61, Apr. 2018.

[17] C. Amza, A. Zapciu, and D. Popescu, "Paste Extruder—Hardware Add-On for Desktop 3D Printers," *Technologies*, vol. 5, no. 3, p. 50, Aug. 2017.

[18] J. T. Muth *et al.*, "Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers," *Adv. Mater.*, vol. 26, no. 36, pp. 6307–6312, Sep. 2014.

[19] W. T. Navaraj, S. Gupta, L. Lorenzelli, and R. S. Dahiya, "Wafer Scale Transfer of Ultrathin Silicon Chips on Flexible Substrates for High Performance Bendable Systems," *Adv. Electron. Mater.*, vol. 4, no. 4, p. 1700277, Apr. 2018.