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Temperature Compensated 3D Printed Strain Sensor for Advanced Manufacturing Applications

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***Abstract*—Additive Manufacturing, has evolved beyond prototyping to manufacturing end-products. The authors are involved in developing a large-scale extrusion-based 3D printer to print mining equipment - a Gravity Separation Spiral, and embedding sensors to monitor the operational conditions remotely. This paper presents a temperature-compensated strain sensor that can be 3D printed inline within large-scale 3D printed equipment. The sensor is printed using conductive carbon filament and embedded in a Polylactic acid (PLA) base. A half-bridge setup is proposed to reduce the impact of temperature variations. Temperature-controlled tests have been conducted with the proposed half-bridge and compared with a non-temperature compensated quarter-bridge setup. Results show that the half-bridge configuration reduces the temperature impact on the strain measurement significantly (68%) compared to the quarter-bridge, in the range of 25-40 °C. Deflection testing conducted on the printed sensor shows a near-linear relationship between bending strain and voltage. Multiple bending cycles have shown that there is no significant hysteresis. ANSYS simulations are used to accurately estimate the internal temperature since embedding a temperature sensor would affect the structural integrity. Although carbon black material is naturally brittle, steps have been taken in the design to avoid undesirable cracking. Results from laser microscopy analysis of the printed traces showed no crack defects.**

***Index Terms*—Advanced manufacturing, Additive manufacturing, 3D printing, Industry 4.0, Temperature compensated strain gauge**

I. Introduction

With the Industry 4.0 revolution encouraging the development of smart, interconnected devices, as well as advances in Additive manufacturing (AM) enabling the creation of viable, bespoke end-products, the world is poised on the brink of an exciting future. There are many advantages of directly 3D printing a physical object from a model generated by a computer when compared to other manufacturing methods, including customisability, the production of intricate and complex shapes, and material waste reduction. According to The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO), up to 70% of costs can be reduced by removing the requirement of tooling [1]. In recent years, various industries such as medical, construction and aviation have already started to incorporate AM [2]–[4].

The mining sector is another important segment of the economy interested in innovations relating to large-scale 3D printing. The authors are involved in a project led by UTS Rapido to develop a 3D printer to print a Gravity Separation Spiral (GSS). These spirals are used in the mining industry to separate minerals from mineral-rich slurry, and usually operate in clusters, called spiral banks, as shown in Fig. 1a. Currently, these spirals are manufactured using mould-based manufacturing techniques, which have some major drawbacks such as limited customisability of the spiral shape, as well as potential worker exposure to hazardous material. Since these GSS operate in various remote parts of the world, it is vital to monitor their operating conditions to understand their production state. Therefore, various embedded sensors are being investigated and integrated into the design to measure various parameters. Embedding 3D printed sensors inside the 3D printed GSS has various advantages, including lower cost, customisability, and the ability to integrate with the structure without significantly compromising its mechanical properties [5]. Already, the authors have developed 3D printable wear, strain, temperature, vibration sensors that can be printed inline and an inlet pipe flow meter [6]–[13]. The team has developed a one-third-of scale printer as shown in Fig. 1b and has nearly completed the full-scale version shown in Fig. 1c. Since printing occurs in a radial layer addition as opposed to traditional vertical printing, the authors have developed a radial slicing algorithm to print helical shape objects and an optimal path planning algorithm for the print head [12], [13].

Fibre Bragg grating (FBG) is a technique that has been used to develop various types of sensors due to advantages such as lower cost, smaller size, simpler structure and immunity to electromagnetic interference [14]. Tanaka et al. [15] have developed a temperature compensated fibre strain gauge with two devices using fibre sensors, thus allowing both strain and temperature to be measured. Ghosh et al. [16] proposed a temperature compensated high-resolution strain sensor based on four-wave mixing. In this work, two chirped FBGs are used so the temperature effect on one FBG is compensated by

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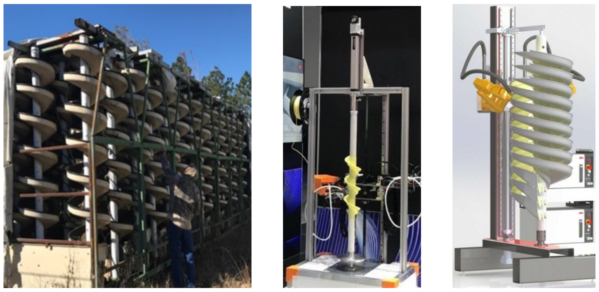


(a) (b) (c)

Fig. 1: a) A bank of GSS. b) One-third-of scale printer. c) Full-scale printer design.

the other FBG. This essentially means that one sensor (FBG) is oriented in a way that makes it immune to the applied strain. In this four-wave mixing method, the applied temperature is in the range of 25-100 °C. Yuan et al. [17] developed a tunable FBG temperature compensated strain sensor with a dual-FBG sensor in a poly (methyl methacrylate) single-mode microstructured polymer optical fibre.

A temperature compensated surface acoustic wave sensor was used as the basis for a wireless and passive strain sensor [18]. Quartz was used due to its excellent temperature stability for the piezoelectric substrate. During the testing, they were able to achieve high sensitivity and good temperature stability.

Using two cascaded Sagnac interferometers, Gu et al. [19] developed a temperature compensated strain gauge. The method used an all-solid hybrid photonic crystal fibre with stress-induced birefringence, offering maximum strain sensitivity, as well as robustness against cross-talk. Their experimental results have shown that their sensor can provide high strain sensitivity and a low-temperature sensitivity.

Strain sensors manufactured using thick-film resistors have been applied in civil engineering because of their sensitivity, stability, low manufacturing cost, and long service life. However, these sensors suffer from thermal sensitivity. To address this Wen et al. [20] proposed a method to fabricate a thick-film resistor strain sensor with low-temperature sensitivity. They used resistance-temperature curves with various materials in the sensor, to understand the effect of temperature.

Carbon nanomaterials are popular in sensing applications due to their tunable properties. However, these sensors are affected by various environmental factors such as temperature. To overcome these problems, Ramalingame et al. [21] proposed a hybrid sensor based on two materials that have positive (graphene) and negative (multi-walled carbon nanotubes) temperature coefficients. By mixing these materials, the hybrid material becomes insensitive to the temperature changes while keeping its strain sensing capabilities.

Zymelka et al. [22] devised a low-cost printed strain sensor array for structural health monitoring applications such as bridges. This enabled the sensor to be used in different seasons to monitor strain in large structures and to identify and localise cracks accurately. The sensor was developed using the screen printing method and required curing of the sensors in a heated chamber. Furthermore, the sensors are fabricated in arrays of sixteen, and developed as a full Wheatstone-bridge strain sensor. The sensor arrays were developed using graphite-based material and therefore, can be manufactured economically. Additionally, the arrays can be scaled in size and shape according to the device size as required.

Using two different types of materials, Daniel et al. [23] proposed a temperature compensated strain gauge. Due to the different thermal coefficient of resistance of two materials, it was possible to distinguish between resistance changes caused by temperature and strain. In the experiment, they used silicon substrate, platinum and titanium for the strain gauge materials, arranging two of the strain sensors close to each other so that both sensors are subjected to the same temperature.

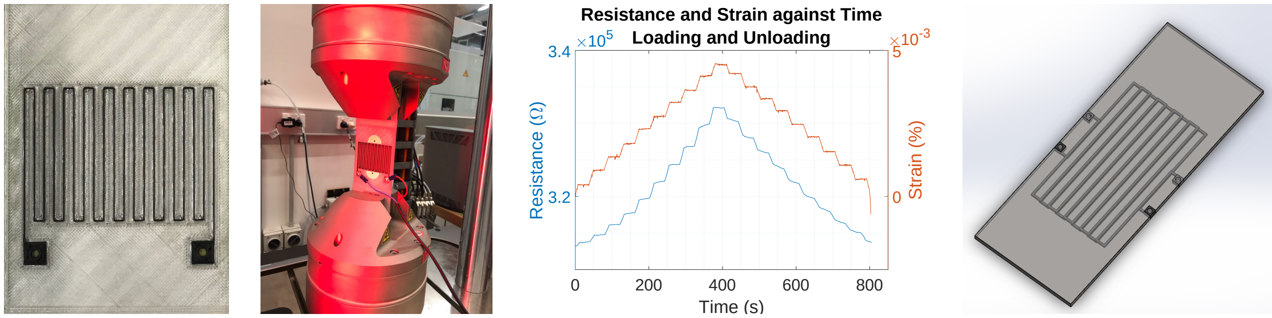
Researchers have used various materials and 3D printing methods to print strain sensors. Maiwald et al. [24] printed strain sensors using the Aerosol Jet® printing method. A polymer isolation layer is printed first, followed by a metal layer, which is then encapsulated to protect the printed sensor. By incorporating this technique, they were able to increase the density of the printed material and achieved high electrical conductivity. Thompson et al. [25] developed an aerosol printing method that atomises a material solution into microscopic particles, which is then deposited on a target surface. To print the strain gauge, they used a water-based conductive polymer, and transferred the solution onto a plastic beam.

Since the GSS operates in places where there are significant temperature changes throughout the year, it is imperative to create a sensor that is temperature compensated. In this research, a carbon-based filament has been used to print the strain sensors due to the low-cost, high availability, and corrosion resistance. Additionally, other sensors such as wear and temperature sensors [6], [8] have been developed using the same material in order to reduce the production complexity. Additionally, different research is underway to identify the suitable location to place these sensors [26]. Contribution of this paper is an extrusion-based temperature compensated strain gauge that can be embedded inside 3D printed objects. The rest of the paper is organised as follows: Section II describes the theory of strain sensors and temperature compensation; Section III presents the experimental results, Section IV provides the discussion of results, and finally, Section V presents the conclusion.

II. Methodology

A. *Measurement of Strain*

Strain can be defined as the amount (ratio) of elongation compared to its original length due to an applied force. There are different types of strains such as axial, torsional, bending and shear [27]. A conventional strain gauge consists of a metallic wire or a thin layer of foil in a pattern (normally a grid) to maximise the axial strain the traces are subjected to. 3D printed conductive carbon traces have been used in this



(a) (b) (c) (d)

Fig. 2: a) Previously tested single strain gauge. b) Testing previous strain gauge using tensile testing machine. c) Test results of the previous strain gauge [7]. d) New temperature-compensated design.

research to replace the metallic traces that are typically found in strain sensors, and are printed directly inside, embedded in the base material.

The resistance, R is given by (1). It is based on the object's length, l and cross-section area, A, and the material resistivity, ρ. When strain is applied to the material, l will increase, reducing A, thus increasing R. The ratio of the change of resistance, $\Delta R/R$ is proportional to the strain, ε. This relationship is expressed in (3), where the sensitivity of the gauge is defined by the gauge factor, GF.

$$R = \rho l/A \tag{1}$$

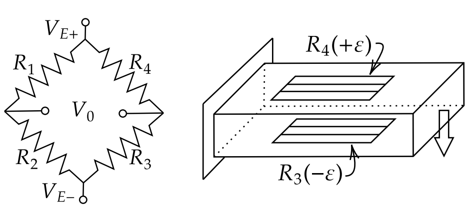
$$\Delta R/R = GF \times \varepsilon \tag{2}$$

B. Temperature Compensation

To measure small changes in the resistance, a Wheatstone bridge-based approach is adopted. The Wheatstone bridge can be explained as two voltage divider circuits in parallel, where one voltage divider circuit contains R_1 and R_2, and the other circuit contains R_3 and R_4 as shown in Fig. 3a. The voltage of the bridge, V_0 can be calculated based on the input voltage, V_E as shown in (3).

$$V_0 = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right] \cdot V_E \tag{3}$$

There are different types of arrangements for strain sensors, namely, quarter-bridge, half-bridge and full-bridge. Quarter-bridge contains one strain gauge where R_4 is the active strain gauge and measure the axial or bending strain. This arrangement is not temperature compensated. The half-bridge configuration can have two different configurations and since we are measuring the bending strain, the arrangement shown in Fig. 3 has been selected. In this setup, R_4 is the active strain gauge measuring tensile strain ($+\varepsilon$) while R_3 is the active strain gauge measuring the compressive strain ($-\varepsilon$) [27]. Incorporating this allows for compensation whilst considering the temperature changes. In this research, the quarter-bridge and half-bridge 3D printed strain sensors have been compared to investigate the effectiveness of temperature compensation.



(a) (b)

Fig. 3: a) Wheatstone bridge. b) Half-bridge setup.

III. Experiment and Results

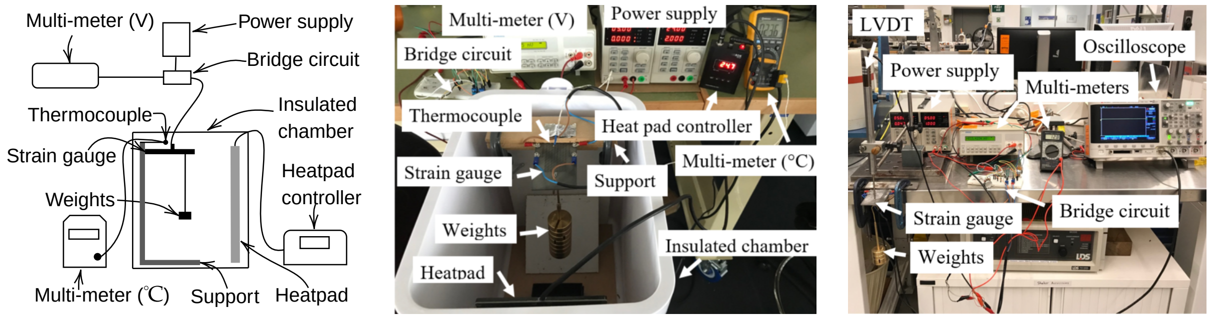
The authors have already printed a single strain gauge (Fig. 2a) and characterised it with a tensile testing machine (Fig. 2b) by measuring the resistance change. Experiments showed a near-linear relationship between resistance and tensile strain, as in the graph (Fig. 2c) [7]. Due to its susceptibility to temperature change, a new half-bridge sensor (Fig. 2d) has been designed (Fig. 3b) to enable temperature compensation of the 3D printed sensor. It is important to note that it was not possible to create a temperature-controlled environment around the tensile testing machine used in [7], and the device was incapable of effectively measuring the bending strain. Thus, a new rig has been developed to overcome these limitations as shown in Fig. 4b.

A. Design and the Material of The Strain Gauge

The 3D model of the sensor is shown in Fig. 2d. The sensor has dimensions of 150 mm x 60 mm x 3 mm for length, width and thickness, respectively. The width of the trace is 1 mm. The two strain sensors were oriented in the same manner as the half-bridge design shown in Fig. 3b and Fig. 6a, which shows a closer view of the printed strain gauge The base material used to print the sensor was Polylactic acid (PLA). Conductive traces were printed using Proto-Pasta conductive PLA. This conductive filament is a mix of carbon black and PLA. The resistivity of the material before printing is 15 Ω.cm, and after printing this increases to 30 Ω.cm along the X-Y plane and 115 Ω.cm along Z-axis.

B. Printing Process

The temperature compensated strain gauge was printed using the Prusa i3 Mk3 printer with the multi-material unit



(a) (b) (c)

Fig. 4: a) Components of the temperature testing rig. b) Temperature testing rig setup. c) Displacement testing rig setup.

2.0 attachment to print two filaments concurrently. This printer is a popular open-source extrusion material printer that can handle five filaments simultaneously. Table I shows the print parameters related to the printing of the sensor.

TABLE I: Print Parameters

Print Parameter	**Value**
Nozzle diameter	0.4 mm
Nozzle temperature (PLA)	210 °C
Bed temperature	65 °C
Nozzle temperature (conductive PLA)	240 °C
Printing speed (PLA)	60 mm/s
Printing speed (conductive PLA)	25 mm/s
Purge volume	700 mm^3

C. Experiment Setup

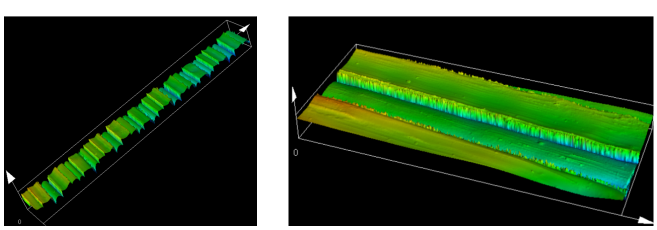
In this experiment, there were two variables to change: temperature and strain. Since temperature should be consistent and needs to be controlled properly, an insulated closed box has been used. To control the temperature inside the box, a heating pad (RDK) with a temperature controller where the temperature can be set properly has been used. A thermocouple connected to a multi-meter was used to measure the temperature inside the box. A set of weights (1 kg) have been used to change the force acting on the sensor which cause strain, adding 200 g in each step. A circuit with half-bridge and quarter bridge has been used to measure the effectiveness of the two different approaches. A voltage of 5V was supplied using a lab power supply and the voltage across the bridge was measured using a 5½-digit multi-meter (PREMA 5017). An overview of the components in the testing rig and their connections are shown in Fig. 4a, and an image of the setup is shown in Fig. 4b.

D. Microscopic Analysis Results

Carbon as a pure material is brittle and form cracks when subjected to strain. These cracks will eventually increase the resistance of the material. Since strain sensors are subjected to strain, an increase in resistance from cracks will affect the measurements. In this research, the filament used was made with carbon black (powder form) mixed with PLA, thus, lessening the chance of crack formation. To validate this concept, a laser microscope (LEXT OLS5000) has been used to observe the printed traces of a previous design (Fig. 2a) after undergoing a tensile test (Fig. 2b). The reason for using the previous design for this test is due to the visible conductive traces found on its surface, enabling observation through a microscope, whereas the new design traces were embedded inside and not visible. The sample results are shown in Fig. 5. Fig. 5a shows a strip of multiple traces and Fig. 5b shows a close-up view of a conductive trace. During this microscope testing, no cracks were detected, proving that conductive traces can handle stress without cracking within the tested strain range in graph Fig. 2c.

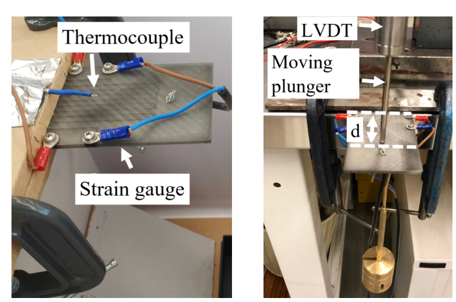
E. Results from Temperature Controlled Test

During testing, for each weight, the ambient temperature of the box was changed from 25 °Cto 40 °C and voltage



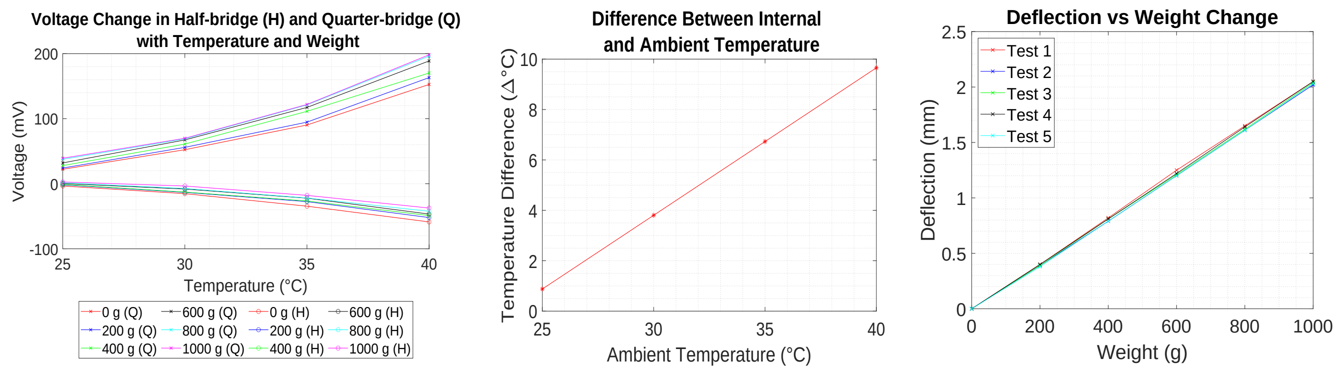
(a) (b)

Fig. 5: a) Microscope depth image of multiple traces. b) Microscope depth image of a single trace.



(a) (b)

Fig. 6: a) Close-up view of the sensor. b) Close-up view of the arrangement of the LVDT sensor.



(a) (b) (c)

Fig. 7: a) Voltage change in half-bridge and quarter-bridge arrangement for different weights and voltages. b) Difference in internal temperature and ambient temperature. c) Close-up view of the printed strain gauge.

values were recorded. Prior to measuring the voltage, each temperature setting was held for 2 minutes to propagate the heat to the sensor. The same test has been conducted for both quarter-bridge and half-bridge arrangements to compare the temperature compensation properties. The results from the temperature controlled test are shown in Fig. 7a. From the graph, it can be seen that the quarter-bridge has an absolute average temperature gradient of 9.85 mV/°C, while the half-bridge has 3.16 mV/°C. The gradient is related to the error caused by temperature thus, higher the gradient, higher error. A lower gradient means that the impact of temperature is comparatively less on strain measurement. This result shows that the the proposed half-bridge method reduced the gradient by 68% compared to the quarter-bridge.

F. *ANSYS Simulation Results*

The printed strain sensors are embedded inside and to measure its actual temperature would also require embedding a temperature probe. Such placement of an external sensor will affect the structural integrity of the material and the bending behaviour of the specimen. Therefore, during testing the ambient temperature was changed and measured. Although, it is important to note that the actual temperature the strain sensors are subjected to are different from the ambient temperature since there is a temperature gradient in the PLA material. To understand this temperature difference, ANSYS simulations have been conducted for each temperature test conducted within the insulated box. The results are graphed as shown in Fig. 7b, where the temperature difference can be observed. In the simulation, the sensor was subjected to each ambient temperature tested previously, from 25 °C to 40 °C, with the maximum internal temperature measured after 2 minutes. Fig. 8 shows the temperature distribution of the sensor in ANSYS for the 40 °C. This test result shows that the maximum temperature difference is around 9.7 °C.

G. *Displacement Testing*

During the temperature controlled testing, the voltage was measured for each weight change because it is not possible to directly measure the deflection when the sensor is in the closed box. To overcome this limitation, a separate setup was used to relate the results with the deflection, as shown in Fig. 4c. In this setup, a linear variable differential transformer (LVDT) is used to measure the deflection. The LVDT (RDC group LDC2000A) sensor was mounted on top of the strain gauge with a distance (d) of 85 mm from the lab bench as shown in Fig. 6b. The bending of the sensor from the applied

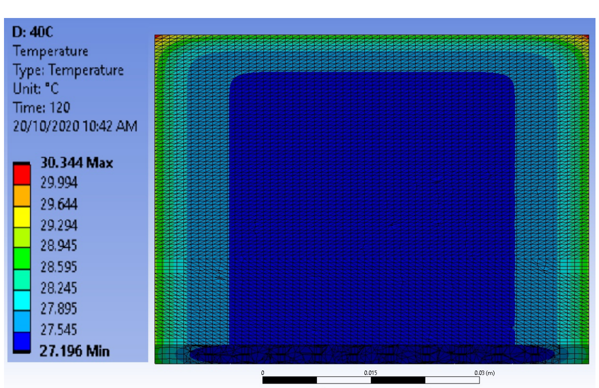


Fig. 8: Simulation result of the internal temperature for the ambient temperature of 40 °C.

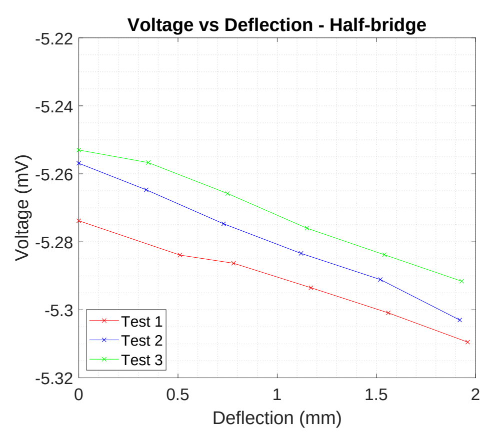


Fig. 9: Deflection testing result for half-bridge.

weight results in a vertical displacement of the plunger in the LVDT sensor, which is then translated to a voltage change measured using a multi-meter. Using the calibration results in the LVDT sensor, the deflection is calculated.

In this setup, two tests were carried out. Firstly, five weighting cycles were conducted to determine if there is measurable hysteresis in the sensor, with the results shown in Fig. 7c. This result shows there is no significant hysteresis in the sensor. Secondly, strain testing with the half-bridge was carried out by measuring the deflection and voltage since temperature controlled testing showed the half-bridge is resilient to changes in temperature. Fig. 9 shows this result. According to the test results, the printed sensor shows a near-linear relationship between bending strain and voltage.

IV. Discussion

A previously developed 3D printed strain sensor showed potential due to the near-linear relationship between the tensile strain and resistance [7]. However, the sensor was susceptible to changes in temperature, which led to inaccurate measurements. Thus, a 3D printable strain gauge resilient to temperature changes has been devised and investigated. Various methods have been proposed in the literature to compensate for temperature in strain sensors. However, few of those methods include FBG [15]–[17], hybrid photonic crystal fibres [19], thick-film resistor-based methods using metal [20], hybrid carbon nanomaterial-based methods[21], screen printing method which required curing [22], and multi-metal-based method [23]. All these methods either use different printing techniques, or require external sensors or added materials that cannot be printed simultaneously. Therefore, this temperature compensated strain sensor has been developed by extrusion-based 3D printing of carbon-based conductive filament. The printed traces of a strain gauge that had undergone testing, were examined for defects using a laser microscope. However, there were no observable defects in the material. The impact of temperature was identified through two experimental setups. A half-bridge configuration of strain sensors has been shown to compensate for the temperature, whereas a quarter-bridge configuration does not. Results showed that the half-bridge approach was around 68% less prone to temperature changes when compared to the quarter-bridge. Theoretically, a half-bridge should be unaffected by temperature. However, during the experiment, there was around 3.16 mV/°C of gradient observed. The reason for this is that, although the designs are similar during the printing stage, the printing process itself introduced around 90 kΩ resistance difference between the two strain sensors. When the temperature increases, the difference in resistance creates an unbalanced bridge, resulting in an observed temperature gradient. During the testing, the ambient temperature was measured since it is not possible to measure the internal temperature of the sensor without compromising the structural integrity. An ANSYS simulation has been conducted to understand the difference between ambient and internal temperatures. The results showed that the maximum temperature difference is around 9.7 °C. In the previous experiment with the old design, the tensile strain [7] of the specimen was tested. However, large-scale printed equipment such as GSS is subject to bending strain. Hence, the deflection was measured in a separate test with a constant temperature and with the same weight range. The deflection was measured using an LVDT sensor where, five bend-and-release cycles were conducted to measure the hysteresis, with test results showing that the hysteresis was insignificant. Different research is underway to determine the durability of the material by testing the abrasion and long term weathering test. Finally, the temperature compensated strain gauge setup (half-bridge) was tested by measuring the deflection and voltage, where the test results have shown a near-linear relationship between bending strain and voltage. Therefore, these results show that the proposed 3D printed half-bridge strain gauge approach is resilient to changes in temperature.

V. Conclusion

This paper presented a 3D printed temperature compensated strain gauge which is printed using carbon-based conductive filament. The sensor was tested in an insulated chamber to carefully control and vary the ambient temperature. Results have shown that the sensor is significantly (68%) less prone to changes in temperature. Strain measurement testing determined that the printed sensor has low hysteresis and that the relationship between the bending strain and voltage is approximately linear. This sensor can be used to embed in suitable 3D printed objects to measure strain with temperature compensation.

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