Strain sensing characteristics of 3D-printed conductive plastics

J. R. McGhee, M. Sinclair, D. J. Southee and K. G. U. Wijayantha

This study electrically characterizes three types of commercially available conductive three-dimensional (3D) printing filament for use in 3D printed functional devices. The three plastics were carbon dispersed acrylonitrile butadiene styrene (ABS), carbon dispersed polylactic acid (PLA) and graphene dispersed PLA. The method of 3D printing used was material extrusion and prints were made in both single and dual extrusion modes. The plastics were found to be piezoresistive, enabling them to be characterized as strain sensors. The electrical characteristics of these materials enabled the measurement of strain using low cost, readily available prototyping equipment and minimising the requirement for dedicated instrument components (e.g. Wheatstone bridges). Increasing the thickness of the plastics improved conductivity. However, this also decreased the reliability and reproducibility of strain sensor data due to a complex internal 3D structure. The recommendation for reliable use in prototyping and manufacturing is to print tracking (under 0.8mm thickness) to produce resistance measurements that are predictable and follow a linear regression up to R2 = 0.9991. A dual extruded 3D print was fabricated as a final demonstration. A force sensing resistor (FSR) interface was created. The final demonstration uses a PIC18F45K20 microcontroller to process sensor inputs, outputting to an alphanumeric LCD.

Introduction: Additive Manufacturing (AM), commonly referred to as 3D Printing, is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. The most prevalent AM technique is Material Extrusion (ME) which is relatively simple and therefore inexpensive, requiring the heating of a polymer filaments (typically polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS)) to melt temperature, before extruding material through a nozzle onto a flat bed. This compares to other AM technologies such as directed energy deposition, powder bed fusion and vat polymerization which utilize high power energy sources (typically lasers) to fuse (powder) or cure (liquid) polymers.

Recently commercial filament manufacturers have introduced polymers impregnated with materials including wood fibres, glass, ceramic, carbon fibre, graphene and metals such as bronze and copper. This experimentation with extruded materials began to spread in 2012 [2] to include conductive materials for developing functional electronic objects. Rather than focusing on extruded molten material, start-up companies such as Voxel8 or NanoDimension focused on dispensing conductive inks. Both these use proprietary silver based inks deposited on to dielectric substrates for the printing of interconnect or Printed Circuit Boards (PCBs).

The first conductive plastics for 3D printing emerged in 2012 with a focus on conductive carbon filler dispersed into PLA [3]. The simplest plastics adapt common ink formulation techniques to polymers. Carbon Black is generally used as conductive filler, and this is melted with a polymer until the percolation threshold has been reached [4]. This is then drawn into a filament, generally 1.75mm in thickness to then be used for material extrusion [5]. As little is known about the variation in electrical properties and characteristics of 3D, layer by layer manufactured 3D electronics. This letter reports the sensing characteristics of 3D printed conductive plastics and their sensing reliability with regards to a change in 3D structure. As a result, rules and limitations can now be provided for the design and fabrication of viable 3D printed strain sensors adding insights from a materials and geometry perspective.

Data and Methods: The 3D printer used was the Flashforge Creator Pro with dual extrusion and heated bed capabilities. Due to the exotic nature of filaments the extrusion nozzles were replaced with Micro Swiss MK10 0.4mm nozzles utilising a low friction nickel composite and the nozzles PTFE guidance tubes were replaced with all metal barrels to create a smooth thermal gradient. The 3D modelling of sensors for printing was performed in the Solidworks (x64, 2016 - SP2.0) computer-aided design (CAD) package. Calibration of the printer was performed by interfacing the printer with ReplicatorG (v0040) – an open source G-code interpreter. Final driving of the 3D printer utilised FlashPrint (v3.14.0) with the stepping motor for the extruder calibrated to print at 152 steps/mm.

The printing resolution is set via two parameters in material extrusion, these are layer thickness (0.1mm) and the amount of solid material filling the 3D object, also known as the infill (100%). Resolution is also dictated by the resolution of the x/y axes (11µm) and the z-axis (2.5µm), however, these are set values dependant on printer design and cannot be changed. The wall thickness which dictates print strength is set at 3 layers (0.1mm per layer).

Three conductive plastic filaments for material extrusion were selected for having three different magnitudes of resistivity: Proto-pasta conductive carbon PLA (a mixture of Natureworks 4043D PLA, dispersing agent and conductive carbon black); Prima carbon dispersed ABS and Black Magic graphene nano-powder dispersed PLA.

Both ABS and PLA require different temperature parameters to print. The carbon ABS was printed with a heated bed temperature of 110ºC and extrusion nozzle temperature of 220ºC, whereas both PLA type filaments were printed with a 45ºC heated platform at 220ºC nozzle temperature.

Sensor strips (100mmx10mm) were printed at varying thicknesses (0.4mm, 0.6mm, 0.8mm, 1.0mm and 1.5mm) for each material. Each material had five sensors printed at each of the five thicknesses, totalling 25 sensors per material. Sheet resistance measurements were taken using a four-point probe (10µa, Jandel HM21) for each thickness and material. Sheet resistances were found to plateau at their lowest values above 1.0mm thickness Fig. 1.

a b

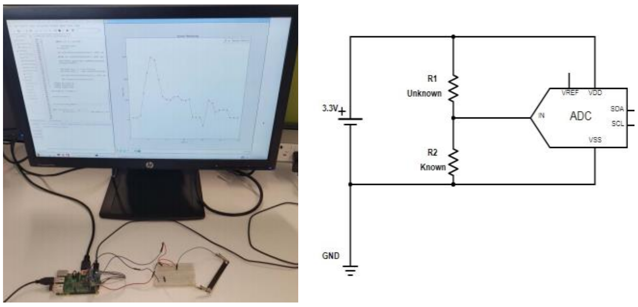
Fig. 1 Four-point probe data and sensor strip, (a) *Sheet resistance vs Sample thickness for carbon dispersed PLA, (b) sensor strip*

Average sheet resistance measurements were then taken five times at 1.0mm for each material alongside average two-point resistances taken using a digital multi-meter (Fluke 179) (Table. 1).

Table 1: Average sheet resistance and two-point resistance with tolerance at 1.00mm thickness

Functional Material	Average Sheet Resistance (Ω/□)	Average Resistance (Ω)
Graphene PLA	20.62	321.20 +/- 5%
Carbon PLA	167.29	1784.47 +/- 5%
Carbon ABS	17540	79550.88 +/- 10%

To determine the materials electromechanical characteristics a study into their strain sensing properties was performed. The underlying resistance of the sensor structures and relative variation from rest facilitates strain sensing measurements without the need for signal amplification equipment (e.g. Wheatstone Bridge). For the measurement of strain sensing data commercially available hardware was used. A Raspberry Pi (2.0) with bespoke software created in Python (v2.7) was used to collect data; this software allows the user to select the voltage applied across the sample as well as the number of samples per second. The change in voltage versus time is output to a csv file for analysis. The Raspberry Pi is then connected to an ADS1015 microchip analogue to digital converter (ADC) connected to the plastic test trip using conductive silver epoxy (RS Components MG Chemical 8331) and a voltage divider circuit Fig. 2.



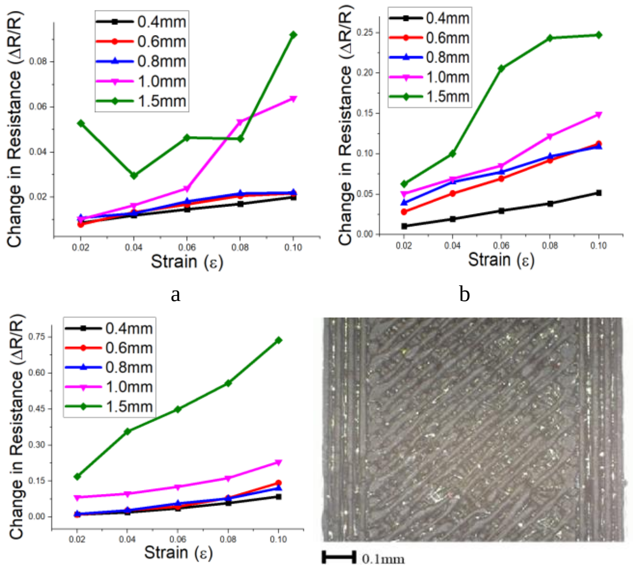
a b

Fig. 2 *Characterisation of sensors and low-profile sensor monitoring platform, (a)RPi connected to sensor strip for voltage change monitoring, (b) voltage divider circuit diagram*

For each thickness of material, 25 controlled bends were undertaken at five different degrees of strain, ranging from 2% to 10% strain. Controlled bends were performed by measuring the change in voltage with regards to strain applied using the equation for strain (eq. 1).

$$\varepsilon = (l_o - l_1)/l_o \qquad (1)$$

The peak change in resistance (ΔR/R) for each bend was plotted against the amount of strain applied for each material and each thickness Fig. 3(a - c).



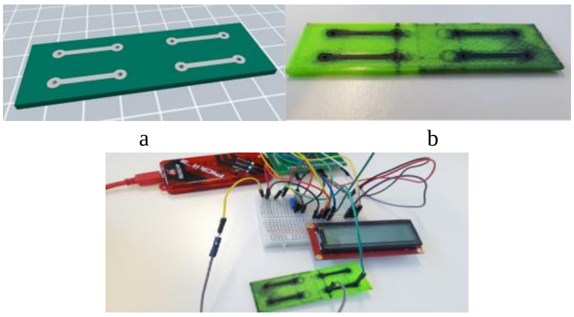
a b

c d

Fig. 3 *Strain applied vs change in resistance at varying material thicknesses, (a) carbon PLA, (b) carbon ABS, (c) graphene PLA, (d) microscope image of printed sensor strip.*

As can be seen in Fig. 3, the linearity and predictability of the strain to resistance change decreases and becomes more erratic with increasing layer thicknesses (>0.8mm). As seen in Table 1, each sensor tested has a different two-point resistance within a measured tolerance. However, change in resistance for all three materials is highly linear regardless of tolerance until layer thickness increases. The proposed mechanism for this is that the behaviour is attributed to how material extrusion printing works, as can be seen under microscope Fig.3(d). The printer works via layer by layer extrusion of molten plastic and instead of creating a uniform solid structure, the 3D structure is made up of a continuous thread of extruded plastic. This creates gaps in thicker layers as the thicker the layer, the further away the top layers are from the heated platform, giving the sensor less time for the 3D structure to become uniform. Upon bending, the gaps in the structure cause some threads to move closer together, improving conductivity, while other threads move further apart, increasing resistance.

To demonstrate use of the conductive plastics in an embedded system using low profile electronics Fig.4(a-c) a 3D model of a strain sensor platform, suitable for 3D printing by dual extrusion (two materials printed at once) was designed. The board had four force sensors which each had 0.8mm holes for the insertion of jumper wires to connect to a PIC18F45K20 microcontroller board. The microcontroller contains a 10bit analogue to digital convertor (ADC) and was programmed via MPLab IDE (v8.76) using C. The board enables the user to press a sensor and output the reading to the LCD screen attached.



a b

c

Fig. 4 *Prototype sensor board, (a) 3D Printing Model, (b) Printed Board, (c) Final prototype using Pickit 3 prototyping platform with PIC18F45K20 microcontroller and display output*

Conclusions: In the conducted work, three conductive plastics for 3D printing have been electrically characterized in terms of piezo-resistivity to determine the reliability of sensing data in embedded systems. It has been found that an increase in the thickness of the sensor leads to a decrease in reliability of measurements for carbon dispersed plastics. All three plastics give stable measurements up to 0.8mm layer thickness. A prototype force sensing resistor platform was printed to demonstrate that due to the relatively high resistivity's of the materials, low profile electronics can be used to create reliable sensor measurements.

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