Feasibility of Additive Manufacturing Method for Developing Stretchable Electronics for Bio-integrated Devices

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1 Background

While the human body is soft and curvilinear with complex, irregular anatomical geometry, established classes of high-performance electronics utilized in medical devices use conventional semiconductor wafer-based technologies that make them rigid and planar. Such a mismatch hinders development of biocompatible devices conformable to human anatomy [1]. This calls for the use of novel electronic materials that provide the capacity for integration into complex integrated circuits. While conventional manufacturing techniques using carbon nanotubes, nanowires, and composite conductive polymer rubbers are effective at creating fully functional stretchable electronics, they are planar, complex, and require prolonged fabrication time, dedicated facilities and infrastructure [2, 3]. Use of cost-effective additive manufacturing processes however, can exploit the power of low-cost 3D printing, enabling a simple, accessible, user-friendly and cost-effective multi-material manufacturing method for creating stretchable skin-like electronic devices that integrate with various parts of the body to create effective bio-integrated devices [4, 5].

This work documents the development and testing of fully functional stretchable and flexible embedded circuits created using additive manufacturing method. A custom-developed syringe-based controlled extrusion process using a conductive silicone material, was used for printing integrated circuits on stretchable substrates. The material characteristics of the silicone under stretching were studied. A proof-of-concept stretchable bio-compatible 'skin' device with an embedded voltage divider circuit was printed and its behavior studied under various working conditions.

2 Methods

An experimental syringe extrusion system was designed to extrude conductive (SS-26S, Silicone Solutions, OH) and non-conductive silicones (2-part RTV Elastosil 685, 7-Sigma, MN) at a constant extrusion rate. The extruder head used a 12V rotary DC motor (Phidgets 3275E) with E4P US Digital Encoder. 2 spur gears (Servo City ½" bore 32 pitch Aluminum gears) were used for linear displacement of a platform on two 1/8th inch lead screws (32 pitch) with a 3:1 speed reduction providing high torque at low speeds for extrusion of highly viscous thixotropic pastes from a plastic syringe (Duda Luer-lok syringe 1ml/20ml) with Luer-lok needle (21 and 16 gauge). An Arduino microcontroller subroutine with H-bridge is used for motor control. In order to implement velocity feedback for steady state volume flow rate, PID control was implemented for the plunger velocity. The complete unit was mounted on to the end of a 6-axis robot, CORVUS [6]. A trajectory-based method issues "start" or "stop" command via serial input to the extruder before the desired start or stop point, as well as desired extrusion velocity.

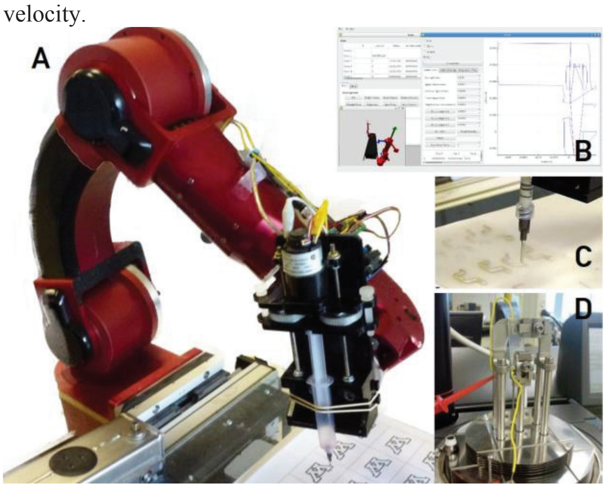

Fig. 1: (A) Custom syringe extruder head mounted on 6-axis robot arm, CORVUS (Medical Robotics & Devices Lab, University of Minnesota). (B) GUI for tool path and extrusion velocity control. (C) Test samples printed with SS-26S on flexible silicone substrate. (D) Material characterization test on a Q800 DMA tester (courtesy 7-Sigma, MN)

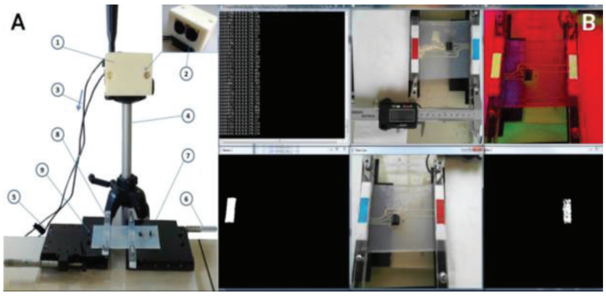

Fig.2: (A) Custom linear translation stage for testing circuit performance under uniaxial strain. (B) Computer vision algorithm (courtesy: Rod Dockter) used to track markers on test sample and determine separation via HSV color detection.

Testing was carried out at 7-Sigma (DMA testing) as well as in Medical Robotics Lab at the University of Minnesota. Material characterization of SS-26S printed traces was done on the Q800 DMA tester (TA Instruments) applying a force ramp of 2N/min and measuring current through the sample (Fig. 1D). Different sizes of conductive traces were printed and the variation of resistance with application of a uniaxial strain was studied for each. Upon studying the conductive properties of SS-26S conductive traces printed on a Elastosil silicone substrate, complete integrated circuits were printed using passive and active electrical components (resistors, LEDs, diodes, etc) using Inkscape to create required printing tool path from the circuit schematic (using Eagle PCB).

Testing of printed complete integrated circuits was carried out on a custom linear translation stage using computer vision to track the elongation of the device.

3 Results

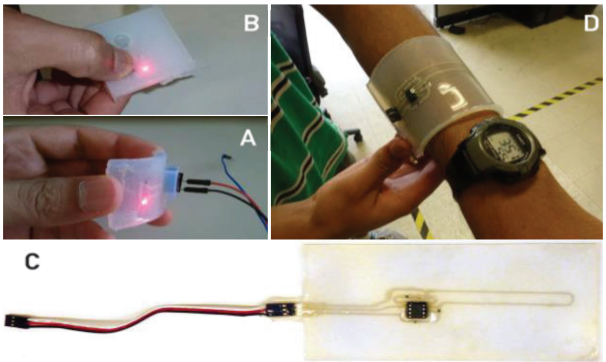

Fig.3: (A) LED circuit working under bending. (B) Self-contained fully-functional circuit with embedded battery. (C) Biocompatible 'skin' device (voltage divider), (D) wrapped on human anatomy.

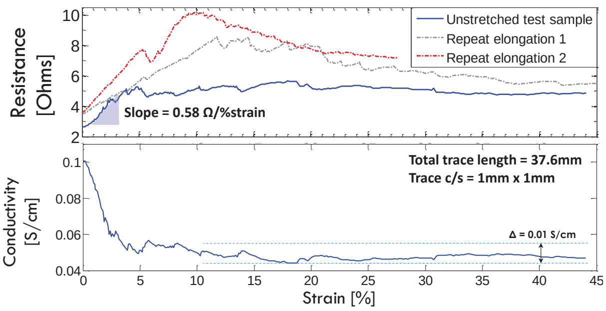

Fig. 4: Resistance and conductivity of the SS-26S test sample under uniaxial strain.

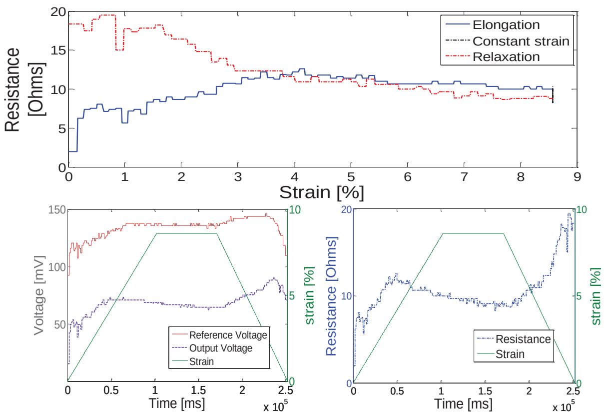

Fig.5: Resistance variation with strain (top) under stretching, constant strain and relaxation; (bottom) voltage output and resistance plotted against time for ramp strain function.

A voltage divider circuit was printed using an ATtiny85 8-pin chip programmed via ArduinoISP. The circuit (Fig.3C) was designed so as to cause change in output voltage upon elongation due to the variation of resistance of the conductive traces in the divider circuit. ADC was used to measure the reference and output voltages and serial communication via Bluetooth (Sparkfun HC-06) was used to collect voltage, resistance and elongation data.

Fig. 4 shows clear variation of conductivity with applied strain, with nearly consistent behavior for different test samples (Fig. 1C). This demonstrates the capability of the SS-26S silicone to act as an effective conductive pathway under elongation in a printed integrated circuit. The plot from the voltage divider stretch test (Fig. 5) shows the variation of behavior of the printed device under elongation and relaxation, indicating the retained functionality of the voltage divider circuit under applied strain.

4 Next steps

3D printing was found to be a suitable manufacturing process for creating fully functional stretchable integrated circuits. From testing various methods for interfacing between electrical components and the conductive silicone traces, it is determined that the reliability of circuit performance could be improved further by ensuring adequate constant electrical contact through isolation of optoelectronic components from applied strain, either through the use of multiple durometer structural silicones or via non-conductive surface meshes.

Future experiments are planned for build and testing of a complete 'skin-like' device like a surgical instrumented glove which can be 3D-printed with embedded sensors and miscellaneous electrical components, custom-built on to clinician's hand to fit the anatomical geometry, utilizing the capability of Corvus to track human anatomy and print on complex and irregular surfaces.

5 Acknowledgment

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