FiberWire: Embedding Electronic Function into 3D Printed Mechanically Strong, Lightweight Carbon Fiber Composite Objects

Saiganesh Swaminathan
Human-Computer Interaction Institute
Carnegie Mellon University
Pittsburgh, PA
saiganes@cs.cmu.edu

Kadri Bugra Ozutemiz
Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA
kozutemi@andrew.cmu.edu

Carmel Majidi
Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA
cmajidi@andrew.cmu.edu

Scott E. Hudson
Human-Computer Interaction Institute
Carnegie Mellon University
Pittsburgh, PA
scott.hudson@cs.cmu.edu

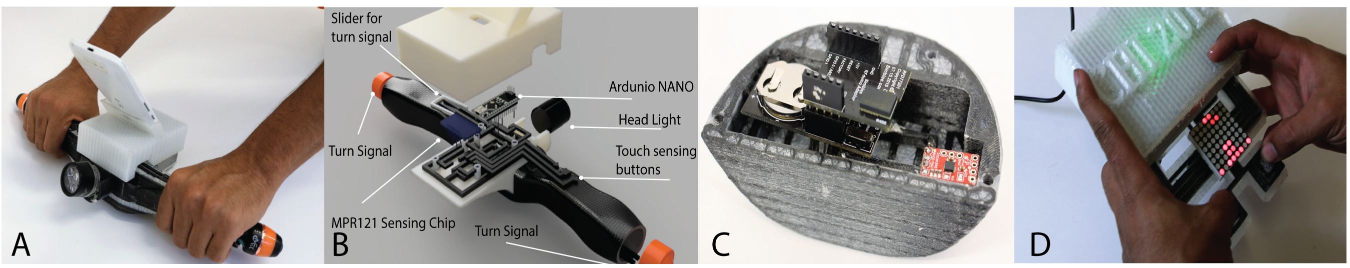

Figure 1: We introduce FiberWire for building interactive devices with embedded multilayer carbon-fiber circuits within mechanically strong objects. a) shows an interactive bike handlebar with embedded circuitry and controls for phone and turn signals b) shows close up view of (rendered) its interior interactive controls and circuits c) shows the bottom face of a golf club with an embedded IMU board for interactive stroke feedback d) shows an interactive game controller with a multi-layer carbon fiber circuit and tactile buttons

ABSTRACT

3D printing offers significant potential in creating highly customized interactive and functional objects. However, at present ability to manufacture functional objects is limited by available materials (e.g., various polymers) and their process properties. For instance, many functional objects need stronger materials which may be satisfied with metal printers. However, to create wholly interactive devices, we need both conductors and insulators to create wiring, and electronic components to complete circuits. Unfortunately, the single material nature of metal printing, and its inherent high temperatures, preclude this. Thus, in 3D printed devices, we have had a choice of strong materials, or embedded interactivity, but not both.

In this paper, we introduce a set of techniques we call FiberWire, which leverages a new commercially available capability to 3D print carbon fiber composite objects. Our technique demonstrates a means to embed circuitry for interactive devices within objects that are light weight and mechanically strong. With FiberWire, we describe a fabrication pipeline takes advantage of laser etching and fiber printing between layers of carbon-fiber composite to form low resistance conductors, thereby enabling the fabrication of electronics directly embedded into mechanically strong objects. Utilizing the fabrication pipeline, we show a range of sensor designs, their performance characterization on these new materials and finally three fully printed example object that are both interactive and mechanically strong – a bicycle handle bar with interactive controls, a swing and impact sensing golf club and an interactive game controller (Figure 1).

CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300797

CCS CONCEPTS

• **Human-centered computing** → *Interaction devices*; Human computer interaction (HCI).

KEYWORDS

3D printing, Carbon-Fiber Composites, Embedded Electronics, Material Processing, Fabrication

ACM Reference Format:
Saiganesh Swaminathan, Kadri Bugra Ozutemiz, Carmel Majidi, and Scott E. Hudson. 2019. FiberWire: Embedding Electronic Function into 3D Printed Mechanically Strong, Lightweight Carbon Fiber Composite Objects. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland Uk.* ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3290605.3300797

1 INTRODUCTION

The rapid growth of new digital manufacturing technologies – most notably additive manufacturing or 3D printing – offers many new opportunities. These techniques can enable users to quickly realize their digital designs in ways that were not previously widely available. For example, 3D printing enables the creation of some geometric forms which are not manufacturable in other ways and can support the manufacture of highly customized products on demand.

As a part of these advances, recent developments in functional 3D printing (in areas such as multi-material printing, printed electronics [6], printed optics [31] and printed metamaterials [13], to name a few) have taken the first steps towards digital specification and fabrication of complete interactive devices. These advances offer the promise that eventually, interactive devices could be highly tailored to the individual or the task, in ways which are not feasible using conventional mass manufacturing techniques.

However, there are a number of limitations in current techniques which need to be overcome to reach this goal. Some of these limitations regard the materials available for 3D printing as well as the ways in which we can achieve multiple functions within one print with those materials. For example, most current print materials (e.g., various polymers) are not structurally strong. In cases where strong materials can be printed (i.e., metal printers) the fabrication processes inherently limit our ability to make interactive objects. Interior circuitry requires the creation of both conductors and insulators in one print, and benefits greatly from an ability to embed prefabricated electronic components – all capabilities that the normally single material have, very high temperature processes of metal printing cannot achieve. This has meant that we have until now typically been forced to choose between printed interior circuitry and mechanically strong printing.

Fortunately, recent advances in new printing materials and processes are starting to provide new alternatives which can overcome these limitations. In this paper we explore the possibilities opened up by one of these new technologies: the ability to 3D print continuous fiber carbon composites. While the strictly in-layer deposition of carbon fiber supported by current technology still produces parts with anisotropic strength properties (i.e., they are much stronger within a print layer than across print layers) they are still very strong, and vastly stronger than typical plastic-based 3D printed objects. For example, typical plastics used for 3D printing such as PLA can have tensile strength up to 50 MPa (in bulk form) [4], compared to 700MPa in carbon fiber composites [2]. Further 3D printed carbon fiber composites offer a range of process advantages such as the ability embed electronics, and support for multi-material printing, that are not found in other 3D printable strong materials. In the work presented here we seek to extend these capabilities in several important ways to move them towards the eventual goal of wholly printable interactive devices (Fig 1).

We first introduce a fabrication process that enables us to use the carbon fibers as conductors to form interior electrical circuits within mechanically strong printed composite parts. This allows us to more easily embed electronics by making the wiring an integral part of the print rather than something added later. Next, we show that sensing techniques which have been highly successful in conjunction with other materials (e.g., sensors based on changes in capacitance [11]), can be readily adapted to this setting. We showcase a range of sensors that can be printed in-situ along with circuitry in carbon fiber composites in a single print. We also demonstrate the performance characteristics of these sensors on new materials such as carbon-fiber composites. Finally, we showcase three full example objects which embody both mechanical strength and are interactive – a bicycle handle bar with interactive controls, a swing and impact sensing golf club and an interactive game controller.

2 RELATED WORK

Our work is situated in the intersection of carbon fiber composite manufacturing processes, its usage in electronics, techniques for electronics prototyping in HCI, and the use of new materials in fabrication.

Carbon-Fiber Composite Electronics and Manufacturing

Traditionally carbon-fiber reinforced composites are manufactured by a hand lay-up process [20] where woven carbon-fibers are stacked layer-by-layer and are impregnated in a resin matrix. Additional approaches to manufacturing carbon fiber composites include pultrusion [20], and selective object lamination [5]. The earliest application of carbon fiber was in the manufacturing of lightbulbs by Thomas Edison in 1879 before being replaced with tungsten. In the later decades carbon fiber composites have been used as a structural material in aerospace, transportation and sporting goods manufacturing due to high tensile strength, and yet very low weight compared to metals.

While the structural applications of carbon-fiber are relatively well known, there is also a body of research examining the use of carbon fibers within conventionally produced composites for electronic purposes. Yuliang et al [9] introduced carbon fiber-based ball-grid array interconnects and investigated how these novel interconnects can be interfaced with conventional circuitry. Lipka et al [18] utilized the high surface area of carbon fibers to fabricate electro-chemical capacitors. To increase the performance of the contact area in potentiometers, a carbon fiber-based design [27] [19] has been explored for sliding contact in potentiometers.

Electromagnetic (EM) applications of conventionally produced carbon fiber composite materials have also been studied, including fabrication of dipole antennas [24] microstrip antennas [7] and electromagnetic absorbers [21]. The key ingredient to enable the possibility of using carbon fiber in electrical and EM applications is the conductivity and shielding effectiveness of fibers, which has been well documented [10]. The electrical resistivity of carbon fibers can range starting from 10 ohm-cm, depending on the number of fibers per unit area and different treatment procedures used. In most electrical applications, the epoxy coating is removed to expose the raw carbon fibers. For example, Jeon et al [15] showed that the contact resistance of carbon fiber composites can be brought down to 0.3 ohms by graining and removing epoxy, then depositing silver. However, the treatment method proposed is tedious and graining procedure need to be implemented manually. In contrast our work introduces a digital fabrication pipeline (use of lasers) that aids in the removal of binder resins, carbonization of the underlying fibers and finally resulting in the reduction of contact resistance in a semi-automated manner.

Another thread of work has looked into how to embed sensing components directly within conventionally produced carbon composites . For example, self-sensing and damage detection [29] has been made possible by embedding strain gauges within carbon fiber composite structures and measuring voltage drops.

The ability to lay down fibers programmatically with 3D printing [3] has opened up possibilities for further research in carbon-fiber electronics. FiberWire makes use of this potential to create carbon fiber circuitry, and introduces an digital fabrication pipeline that enables an effective conductivity to fabricate a range of interactive devices with electrical components.

Electronics Prototyping and Sensor Fabrication in HCI

A wide range of literature in HCI has looked at how to enable fabrication of sensors and electronic circuits. As only a few examples: Midas [25] introduced a software and hardware toolkit to fabricate custom touch sensors using copper tape and a vinyl cutter.

InstantInkjet Circuits [16] demonstrated the capability of printing circuits on an off the shelf inkjet printer by modifying the printer to deposit silver ink and thermally sinter them to form circuits. Circuit stickers [12] introduced a method for attaching electrical circuits to large contact area stickers that are flexible. PaperPulse [23] similarly used an inkjet technique to lay circuit designs on paper and allowing designers to customize and assemble them quickly to form widgets like slider, radio button, etc. on paper. Finally, Printem [30] introduces a new technique to create one-off printed circuit boards with copper by selective curing UV adhesive stacked on top of copper.

More recently, Capricate [26], introduced a fabrication pipeline to design and 3D print capacitive touch sensors. Similarly, Voxel8 [6] is a multi-material printer capable of printing thermoplastics and conductive silver epoxy to form 3D printed embedded electronic devices. However, all these approaches rely on materials such as paper, plastic, etc., which are not structurally strong. One notable exception is [28] which describes several sensors assembled with the help of 3D printed metal parts (but not printed in-situ).

In the work presented here, we demonstrate how the kinds of sensing which have been highly successful in prior work can be integrated into a 3D printer process producing structurally strong objects such as an interactive golf club, bike handlebars, etc –all applications where strength is highly important.

Engineering Material Capabilities in HCI

Recently HCI researchers have started looking at leveraging mechanical and material properties to enable designers to fabricate a wide variety of custom interactive devices. Metamaterial Mechanisms[13] investigates how to design internal microstructure of an object computationally in order to achieve a desired output mechanical movement. In follow-up work, digital mechanical metamaterials [14] investigated how to fabricate simple non-electronic computational objects using a bi-stable spring mechanism for signal propagation. Truss fab [17] enables non-engineers to fabricate large-scale structurally sound structures from desktop 3D printers by offering an integrated software and hardware design toolkit. Cillia [22] presents a novel method to fabricate micron scale hair-like structures using Stereolithography (SLA) onto a range of geometries that can later be utilized

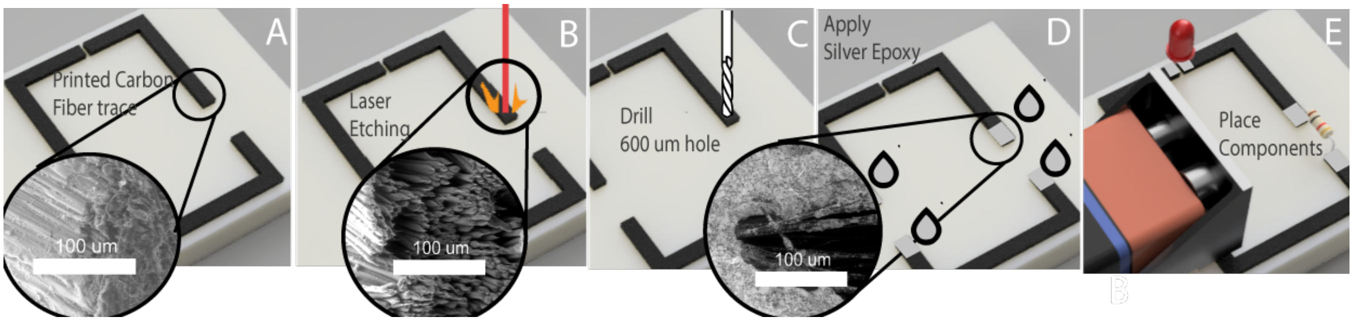

Figure 2: FiberWire Fabrication workflow: (a) 3D printing of carbon-fiber trace circuit, inset shows SEM image of the carbon-fibers bonded with epoxy in the resin matrix (b) Laser etching of epoxy to expose raw carbon fibers, inset shows results of laser etching (c) Drilling micro holes for interfacing with electronic component pins (d) Deposition of silver epoxy on exposed carbon fiber, inset shows carbon fibers are coated with conductive silver and (e) Placement of the components

for both passive actuation and acoustic sensing. Similarly, Yao et al [32] introduced biologic, a system that lets designers embed nano-scale bio actuators using bacteria that responds to humidity.

3 FIBERWIRE FABRICATION PIPELINE

In this section, we introduce the steps involved in fabricating structurally strong, interactive carbon composite electronic devices. The fabrication process of FiberWire consists of 5 major steps: (i) 3D printing of carbon-fiber composite structure with traces, (ii) selective laser etching of epoxy to expose raw carbon fibers on printed traces (iii) drilling micro holes for interfacing with electronic component pins (iv) deposition of silver epoxy on exposed carbon fiber and (v) placing the components. Next consider the steps in detail.

Printing Traces

The fabrication process of FiberWire utilizes the Markforged (MarkTwo) multi-material 3D printer [3] that can programmatically lay out long strand carbon fiber (pre-impregnated with a heat sensitive epoxy resin) as well as other dielectric material such as nylon. The fabrication process begins with a geometric model of an object with embedded circuit traces which is loaded into the unmodified printer software [1]. In addition to specifying base geometry, the software allows us to fill the geometries with both carbon fiber composite and nylon, with an ability to selectively specify layers with different orientations and directions. After experimentation with available settings, we determined that good results could be obtained in single layer traces with a width of at least 3mm.

The printed electrical trace consists of continuous fibers laid along the path of the trace. A close look at the trace using a scanning electron microscope (SEM) (Fig 2A inset) reveals that the carbon fibers are held together in an epoxy resin matrix. However, the epoxy that holds the fibers also reduce the conductivity into and between the fibers.

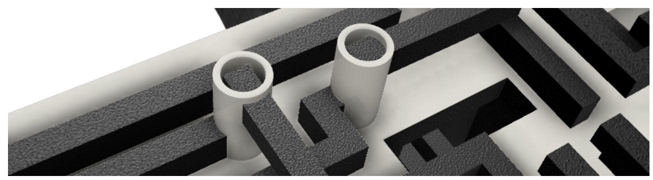

Figure 3: Shows cylindrical via printed between traces layers

Laser Etching

To remove the epoxy and establish better electrical contact, we programmatically pause during the printing of each circuit layer and use laser etching to remove the epoxy (Figure 2 B) from positions of external contacts and vias. As can be seen from the SEM imagery in Fig 2B inset, the raw fibers are exposed as result of this etching process. During this etching process the epoxy is burned away and the raw carbon fibers underneath are carbonized.

In the work reported here, we used a stand-alone commodity CO2 laser cutter (Universal PLS6.150D) in raster mode (12% speed and 100% power) for laser etching. Markforged printer's print bed has magnetic alignment pins (10um accuracy) that allows us to stop printing at a specified layer, take the partially printed object out with the print bed and switch to laser cutter. However, it should be straight forward to integrate a high-power laser diode directly into a similar printer for this purpose in the future.

Holes, Silver Epoxy & Components

After laser etching, we mechanically drill holes of 0.6mm diameter on the trace (Figure 2 C), this enables us to connect the off-the shelf electronic components. While the removing the epoxy improves the conductivity, there is further contact

[1] www.eiger.io

resistance between pins and raw fiber traces. Hence, we coat silver epoxy (2-part MG chemicals 8331) on areas where electrical components need to be inserted (Figure 2 D).

Finally, we place the electronic components by inserting them into the holes, bonding them in place with silver epoxy (Figure 2 E). The silver epoxy helps form better electrical connections with the components by reducing the contact resistance and also structurally supports our components, ensuring they are mechanically bonded well with the traces.

Printing Vias:

We printed vias as cylindrical holes in nylon with traces from each layer leading into these cylinders (Figure 3). To further establish better contact between carbon fiber layers above and below, we laser etch the traces within the cylinders. Finally, we fill the via cylinders with silver epoxy to keep the traces in place and further improve conductivity. Our via designs worked well with a measured resistance less than 2 Ω.

4 BASIC ELECTRICAL PERFORMANCE

Conductivity in Single Layer Traces

To characterize the performance of our fabrication approach, we tested 6 samples of varying lengths 5, 10, 15, 20, 25 and 30cm (maximum length of the printer) for three conditions: a) resistance with original epoxy b) resistance after laser etching b) resistance after laser etching and silver epoxy deposition. We used a 2-point resistance measurement for estimating resistances. We found that in all sample lengths better conductivity is achieved when traces are both treated with laser for epoxy removal and deposited with silver epoxy. As explained in the fabrication pipeline, the observed effect is due to exposition of conductive raw carbon-fibers and the reduction of contact resistance by silver. We summarize the test results in (Table 1).

Further, the mean resistivity for our cross sectional area ($4.995 mm^2$) was found to be 3.669×10^{-4} Ωm ($SD = 9.1 \times 10^{-5}$). Also, from the (Table 1) a linear regression on the silver epoxy condition found the overall fit to be r^2=0.929. The constant coeffcient (contact resistance x 2) was measured to be 3.41 Ω

The results indicate that, it is possible to fabricate highly conductive carbon-fiber traces at the maximum length of the printer with resistances which compare much better than current conductive material approaches employed with polymers.

Conductivity Between Multiple Layers

Conductivity between the layers for fabricating multi-layer circuits was also tested. We printed traces with steps of varying thickness (1 step = 1.625mm). We ran resistivity measurements on samples with 2 steps and 3 steps (Figure 4). We

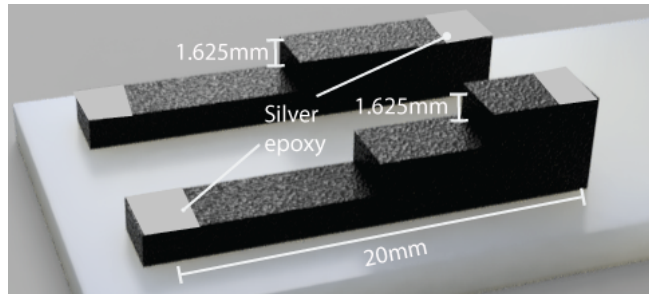

Figure 4: Resistance characterization test between layers

observed a mean resistance of 28.2 Ω (*N* =5, *SD* = 4.09) for 2 step and 75.32 Ω (*N* =5, *SD* = 3.03) for 3-step (after laser etching and silver deposition in the marked areas). The results indicate that the increase in resistance across Z-direction is due the epoxy in between layers.

5 SENSOR DESIGNS

Taking advantage of the FiberWire fabrication process, we provide a range of custom sensor designs that can be fabricated with carbon-fiber composites and be embedded with electrical circuits. Each of these designs makes use of a capacitive sensing [11], thus demonstrating that our materials and processes can easily support integration of this widely used, successful and well supported sensing approach. In this section we illustrate our sensor designs and provide performance characterization of sensors within objects created by our process.

Sliders

We designed sliders with carbon fibers acting as capacitor plates. The sliding element (Figure 5 A) moves across the rails of the slider to support this motion. One of the triangles underneath the sliding element is connected to ground and the other is connected to one of the pins of the sensing circuit. As the sliding element moves (Figure 5 B) the active area of the capacitor changes and as a result the capacitance of the system changes. We capture this change by using an

Table 1: Resistance characterization tests

Lengths (cm)	Printed Carbon Fiber (Ω)	Epoxy Removal (Ω)	With Silver (Ω)
5	90	33.1	5.3
10	120.4	35.4	7.9
15	130	40.6	10.9
20	118	43.6	12.4
25	149.4	44.3	17.1
30	175	48.5	15.8

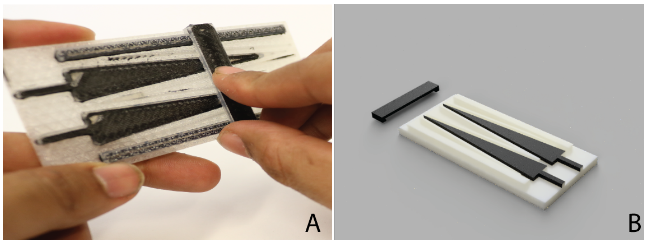

Figure 5: a) Shows the sliders fabricated with FiberWire. We used a triangular design varying the capacitor plate area b) Shows the assembly of the slider. Note that prints of all printed examples have been done using a white nylon base with black carbon fibers to make material placement apparent.

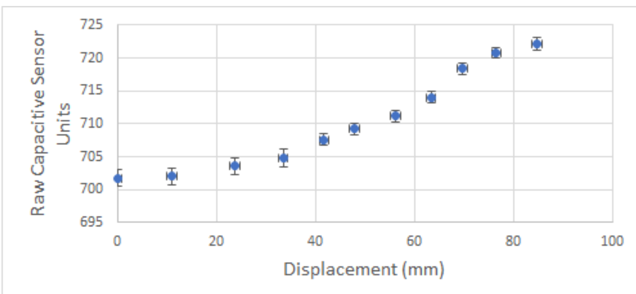

Figure 6: Shows the characterization of capacitance vs displacement behavior of our slider across the device

Arduino and an MPR121 capacitive sensing chip (which has 12 sensing pins sampling at a framerate of 29 Hz).

The MPR121 reports a digital value proportional to the capacitance at the input. We observed a change of 20 raw sensing units (on a scale of 0 to 1023) from one end of the slider to the other. (Figure 6) shows a slightly non-linear relation between the distance of the slider to the thick end of the triangle and capacitance. We repeated the characterization test 12 times to estimate the accuracy of the measurements. Although the change in values over the entire range is relatively small (20 units), the accuracy of each measurement is within 1 unit002E

Rotary Encoders

We also developed a rotary encoder which senses the capacitance change as a conductive plate moves between ground and sensing plates located in the casing. We fabricated the casing to be half filled with carbon fiber and the rotating plate to be completely filled (Figure 7), hence the rotary encoder can sense angles between 0-180 degrees. When the knob is rotated and the plate moves between the casing sensing and ground plate, it results in a change in capacitance. We characterize the behavior of the knob sensor in the same way

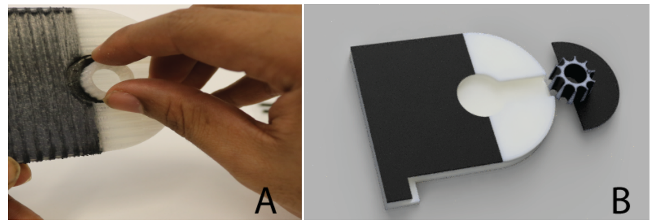

Figure 7: a) Shows the rotary encoders fabricated with FiberWire. The casing includes partially filled carbon fiber in semi-circle and the knob fully filled with carbon fiber b) Shows the assembly of the encoder

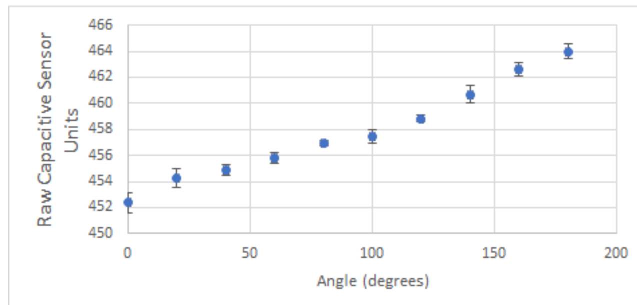

Figure 8: Shows the characterization of capacitance vs angle of our rotary encoder design

as the slider. The (nearly) linear relation between the angle of the knob and the capacitance is given in (Figure 8). The characterization test was repeated 8 times and the accuracy was found to be within 1 unit across those trial

Capacitive Touch Buttons

Because of the nature of 3D printing, we can fabricate custom touch sensors in any geometry we would like. Once designed, a range of custom shapes can be filled with conductive fibers during the print. The sensors could additionally be covered or filled with nylon layers. We use this method to print touch

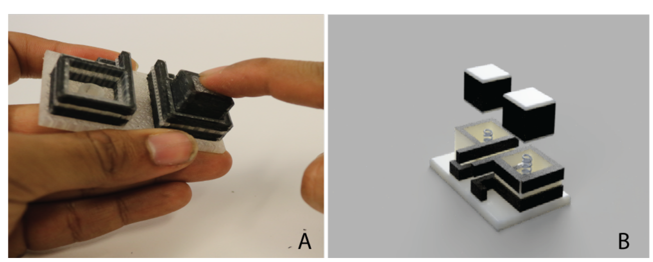

Figure 9: Shows the fabricated tactile buttons with two fiber traces embedded with a nylon layer in the middle. b) Shows the caps that go with the buttons which are also fabricated with carbon fiber

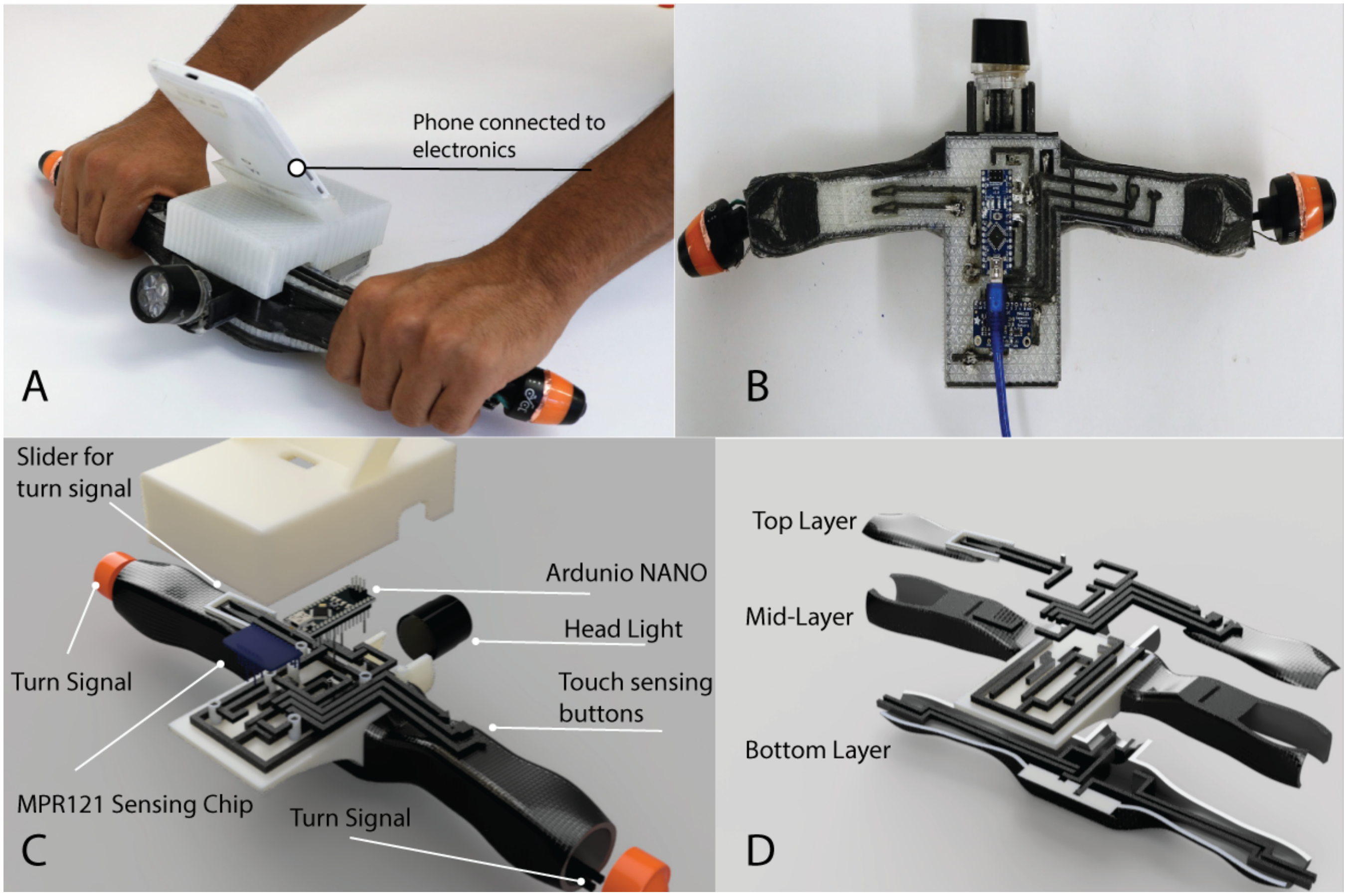

Figure 10: A user holding a full body bike handle bar with embedded carbon fiber circuitry and touch controls. b) Shows the top view of the circuit with components placed on top of the circuit. c) Shows an exploded view of the electronic components which include: headlight, turn lights, and printed touch controls, printed slider, Arduino Nano microcontroller, MPR121 touch sensing board and mobile phone casing. d) Shows three layers that go into the handle bar circuitry printed over layer by layer and connected by vias.

sensitive buttons in different shapes of pause, play and stop buttons in our example applications

Tactile Buttons

We fabricated tactile buttons with a plunger that is loaded with a printed spring and moves in between two capacitor plates (Figure 9). We measured the change in capacitance in the same way as the slider and the rotary encoder. We set a threshold for the capacitance change to detect whether the button is pressed or released and across 200 trials for each button and they worked with 100% accuracy.

6 EXAMPLE APPLICATIONS

In this section we detail three example applications that are both structurally strong and contain integral interactive controls. All our examples utilize the FiberWire fabrication workflow and sensor designs introduced earlier.

#1 A bike handlebar with embedded touch sensors, and lights

We envision using FiberWire techniques in an automated way to create many mechanically strong carbon fiber composite objects such as bicycles, calipers, drones, sporting gear etc. with printed multi-layer electronic circuits and interactive controls embedded inside of them. We show a proof-of-concept: a carbon fiber bike handlebar (Fig 11) printed with interactive controls and embedded electronics using FiberWire fabrication techniques.

Overview of Traces: We 3D printed all the layers of the bike handle bar including the three layers of circuitry embedded inside (Figure 10 A and D) in a single print. The circuits in the bottom most layer (Figure 10 D) consist of 3 pairs of traces, with each pair of traces connecting to ground and a digital pin from a microcontroller. They are routed to turn

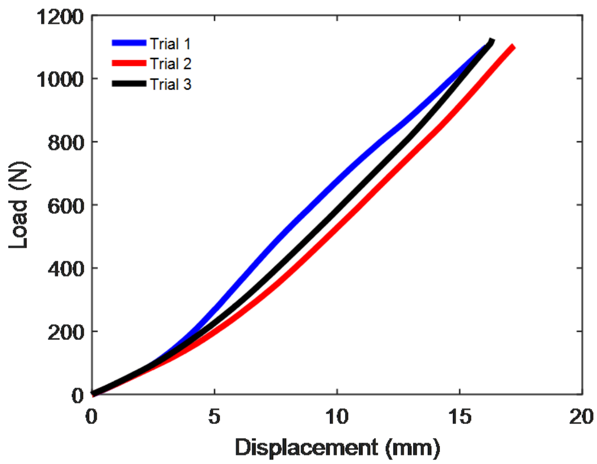

Figure 11: Bike Handle Bar Strength Testing

signal lights at the left and right side of the handle bar and another pair of traces route to the headlight for the bike handle bar. The middle layer (Figure 10 D) of carbon fiber composite circuits are connected to the top layer and bottom layer through vias (Figure 3). All our electronic components are housed in the top most layer of the circuit.

Electronic connections: All our electrical connections are made possible through the FiberWire fabrication workflow described earlier. In this section, we detail how the traces are connected with the electronic components.

In our bike handle bar example, we placed an Arduino Nano microcontroller (Atmega 328p) (Figure 10C) and interfaced it with a MPR121 capacitive touch sensing chip on a separate board. The sensing chip interfaces (I2C & Power) with the microcontroller through our carbon fiber traces printed using FiberWire fabrication process. Further, we printed traces from the MPR121 board to run along the top surface near the right side of handle bar grip towards three touch sensing buttons. The touch buttons consist of play, pause and stop which control the music player in a connected phone using the microcontroller over a serial connection.

On the left side of the handlebar grip (Figure 10 C), there is a capacitive slider that is connected to the MPR121 board which controls the turn signals in the bottom layers of the handle bar.

Finally, to power all the electronic circuitry we use a commodity mobile phone and connect the microcontroller to the phone through an OTG-USB cable. The mobile phone sits in a printed casing shown in Figure 10 A.

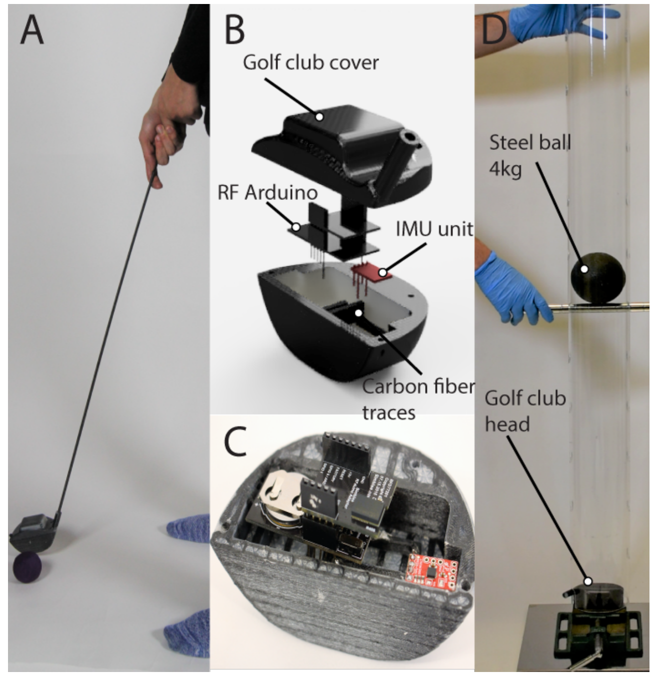

Figure 12: a) Shows the golf club with a user b) Shows the exploded view of golf club with RFduino and accelerometer c) Shows the top view of the fabricated sample d) Shows the drop ball impact test of the golf club head.

Evaluation of Strength: We tested the mechanical strength of our bike handlebar using an Instron 5969 universal material testing machine. We clamped the center of the handlebar to the testing machine and applied an increasing load to one of the handles until the deflection of the handle prevented the tester from applying more load. (The handle did not break during testing, or in fact show any visible signs of damage.) Referring to Figure 11, the maximum load at this point is measured as 1110±11 N. For comparison, the maximum load applied to a handle bar in off-road trails has been reported as 200 N [8].

#2 An interactive Golf club with embedded IMU and RF Microcontroller

We fabricated a golf club that trains people to make good golf strokes with interactive feedback (Figure 12A). The golf club consists of a multi-layer carbon fiber circuit embedded with an IMU, a Bluetooth capable Arduino module (Simblee) and a coin cell battery unit (Figure 12(B-C)). The IMU unit is an MPU-9250 9-axis MEMS sensor, that returns acceleration values upon impact and stroke. The IMU is interfaced with the Bluetooth module which sends the data to a Phone or other Bluetooth connected device.

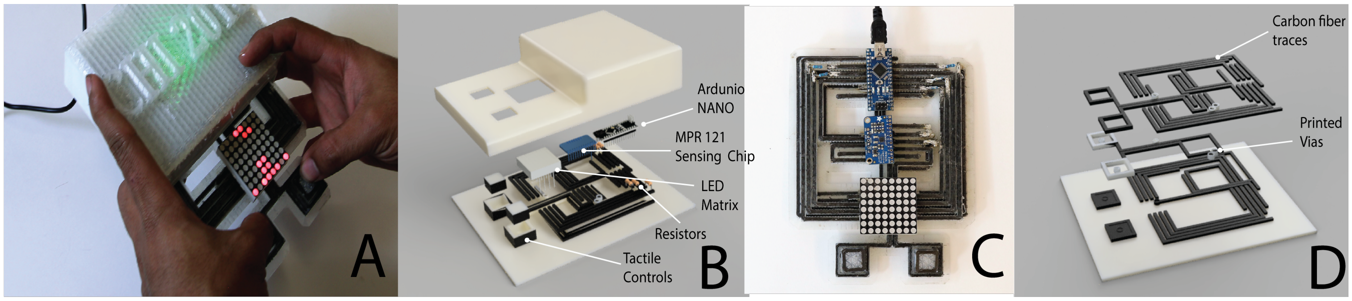

Figure 13: a) A user holding an interactive game controller with two tactile buttons that help play a âĂIJSuper MarioâĂİ game with the LED matrix. b) Shows the exploded view of all the components that are housed inside the game controller i.e., LED matrix, Resistors, Arduino Nano, MPR 121 capacitive sensing board. c) Shows the components placed in the circuit from top view. d) Shows multiple layers of carbon fiber circuits that connect the electrical components, and capacitive sensing tactile buttons.

Evaluation of Strength: We test the impact strength of our golf club by dropping a steel ball with a mass of 4 kg from heights starting from 10 cm and increasing with 10 cm steps until the club breaks (Figure 12D). By doing so we increase the impact energy delivered to the golf club by simply increasing the initial potential energy (which changes linearly with the height and the mass of the ball). We chose to test the golf club with impact instead of simply loading as we did for bike handlebar since the golf club operates under impact conditions (hitting the golf ball).

To compare the impact strength of 3D printed carbon-fiber composite, we repeated the same test with a 3D printed PLA & ABS golf club. We chose the density of the filling of PLA & ABS to the maximum during 3d printing. The masses of the carbon fiber golf club and PLA golf club are measured as 128 gr and 160 gr, respectively. The carbon fiber golf club failed at a drop height of 60 cm (initial potential energy of 23.54 J) while PLA & ABS golf club failed at a drop height of 30 cm (initial potential energy of 11.77 J). We repeated the experiment two times (with newly printed golf clubs) and obtained the same result. Our experiment results show that the 3D printed carbon fiber composite has double the impact strength of the 3D printed PLA/ABS despite being lighter in weight.

#3 An LED "Mario" game with tactile switches

As an additional application we fabricated an interactive game controller (Figure 13A) with multi-layer carbon fiber circuitry. The game controller consists of an LED matrix, an Arduino Nano to drive the LEDS (with firmware implementing a 64-pixel approximation of a "Mario" game), resistors and an MPR121 board to offer capacitance sensing. All components are connected through multi-layer carbon fiber circuitry as seen in Figure 13B. The LED matrix display shows "Mario" as a red led dot and the level maps are displayed using the 64 LEDs as a small display. As the user pushes the tactile button on the right side of the game controller, the Mario dot moves to the right. The left side tactile button is used for controlling the jumps of character.

7 DISCUSSION AND LIMITATIONS

There are a few limitations in our approach to embedding electronic function into carbon-fiber composites. First, our current workflow to embedding circuits on 3D objects is done manually using solid modeling tools (Solidworks, Fusion, etc). We design trace geometries and then create SVG layers for laser etching on specific sites of the traces. The process could be streamlined in future by having a design tool to simultaneously accept existing trace files – gerber files – and 3D geometeries to automatically identify contours of the object to merge with trace routes. Similarly, in a semi-automated manner programmatic pauses could be inserted by the tool to support switching between laser cutter and printer.

Second, printing time for objects is similar to other FDM processes. The golf club head prints in 16 hours. In between the laser etching process takes about 10 secs for each trace and an entire layer 2-3 minutes (if it contains several electrical connections). This could be further improved by integration of multiple processes (laser and print) into a single machine.

Finally, access to continuous fiber fabrication machine may be limited due to early adopter pricing, however in future costs may further go down as new competitive printers [1] are introduced. Furthermore, FiberWire fabrication approach may also be used in a DIY setting by using other manufacturing methods such as hand-layup [20] for fabricating composites. Users can manually stack layers of woven carbon-fiber (conductive) with other fibers such as glass fibers (non-conductive) and selectively apply epoxy to form circuitry and composite devices.

8 CONCLUSION AND FUTUREWORK

With FiberWire, we have introduced new capabilities to engineer carbon fiber-based circuitry inside of mechanically strong parts. We described a repertoire of methods that exploit the electrical characteristics of carbon fiber composites – specifically, demonstrating how to fabricate carbon fiber composite objects with embedded multi-layer circuitry which can directly support the kind of capacitive sensing that has been successful in other fabrication processes. We envision our methods of laser etching and silver deposition could be incorporated directly into a future carbon fiber printer since the current printer already supports a precision motion platform with two types of deposition heads. Specifically, similar printer hardware could also include a high-power laser diode (for etching) and a paste deposition pump (for silver paste). By utilizing our techniques, we hope engineers and designers can fabricate structurally sound and functional interactive objects in the future.

9 ACKNOWLEDGEMENT

We would like to acknowledge Navid Kazem for training the authors to use Instron testing machine. William Pingitore on his advise for impact test setup, Zheng Luo for his help with shooting golf club demo. This work was funded in part by the National Science Foundation under grant IIS-1718651.

REFERENCES

[1] 2019. ANISOPRINT. http://anisoprint.ru/. [Online; accessed 6-January-2019].

[2] 2019. Carbon-fiber Strength Data. https://static.markforged.com/markforged_composites_datasheet.pdf. [Online; accessed 6-January-2019].

[3] 2019. Markforged Product Details. https://markforged.com/materials/composites/. [Online; accessed 6-January-2019].

[4] 2019. PLA Strength Data. http://tinyurl.com/PLAVoxel8. [Online; accessed 6-January-2019].

[5] 2019. SLCOM1. https://envisiontec.com/3d-printers/slcom-1/slcom-1/. [Online; accessed 6-January-2019].

[6] 2019. Voxel8. https://www.voxel8.com/. [Online; accessed 6-January-2019].

[7] Rodrigo R de Assis and Ildefonso Bianchi. 2012. Analysis of microstrip antennas on carbon fiber composite material. *Journal of Microwaves, Optoelectronics and Electromagnetic Applications* 11, 1 (2012), 154–161.

[8] Davis S De Lorenzo and ML Hull. 1999. Quantification of structural loading during off-road cycling. *Journal of Biomechanical Engineering* 121, 4 (1999), 399–405.

[9] Yuliang Deng, Michael G Pecht, Joseph A Swift, and Stanley J Wallace. 2007. Carbon fiber-based grid array interconnects. *IEEE Transactions on Components and Packaging Technologies* 30, 4 (2007), 716–723.

[10] RW Evans. 1997. Design guidelines for shielding effectiveness, current carrying capability, and the enhancement of conductivity of composite materials. (1997).

[11] Tobias Grosse-Puppendahl, Christian Holz, Gabe Cohn, Raphael Wimmer, Oskar Bechtold, Steve Hodges, Matthew S Reynolds, and Joshua R Smith. 2017. Finding common ground: A survey of capacitive sensing in human-computer interaction. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3293–3315.

[12] Steve Hodges, Nicolas Villar, Nicholas Chen, Tushar Chugh, Jie Qi, Diana Nowacka, and Yoshihiro Kawahara. 2014. Circuit stickers: peel-and-stick construction of interactive electronic prototypes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1743–1746.

[13] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. 2016. Metamaterial mechanisms. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 529–539.

[14] Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch. 2017. Digital mechanical metamaterials. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 977–988.

[15] Eun-Beom Jeon, Takahiro Fujimura, Kosuke Takahashi, and Hak-Sung Kim. 2014. An investigation of contact resistance between carbon fiber/epoxy composite laminate and printed silver electrode for damage monitoring. *Composites Part A: Applied Science and Manufacturing* 66 (2014), 193–200.

[16] Yoshihiro Kawahara, Steve Hodges, Benjamin S Cook, Cheng Zhang, and Gregory D Abowd. 2013. Instant inkjet circuits: lab-based inkjet printing to support rapid prototyping of UbiComp devices. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*. ACM, 363–372.

[17] Robert Kovacs, Anna Seufert, Ludwig Wall, Hsiang-Ting Chen, Florian Meinel, Willi Müller, Sijing You, Maximilian Brehm, Jonathan Striebel, Yannis Kommana, et al. 2017. Trussfab: Fabricating sturdy large-scale structures on desktop 3d printers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 2606–2616.

[18] Stephen M Lipka. 1997. Electrochemical capacitors utilizing low surface area carbon fiber. *IEEE Aerospace and Electronic Systems Magazine* 12, 7 (1997), 27–30.

[19] Shengli Liu. 2001. Carbon fiber contactor in polymer resistive position sensors. In *Electrical Contacts, 2001. Proceedings of the Forty-Seventh IEEE Holm Conference on*. IEEE, 282–287.

[20] Pankar K Mallick. 2007. *Fiber-reinforced composites: materials, manufacturing, and design*. CRC press.

[21] CP Neo and VK Varadan. 2001. Design and development of electromagnetic absorbers with carbon fiber composites and matching dielectric layers. *Smart materials and structures* 10, 5 (2001), 1107.

[22] Jifei Ou, Gershon Dublon, Chin-Yi Cheng, Felix Heibeck, Karl Willis, and Hiroshi Ishii. 2016. Cilllia: 3D printed micro-pillar structures for surface texture, actuation and sensing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 5753–5764.

[23] Raf Ramakers, Kashyap Todi, and Kris Luyten. 2015. PaperPulse: an integrated approach for embedding electronics in paper designs. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2457–2466.

[24] Elliot J Riley, Erik H Lenzing, and Ram M Narayanan. 2014. Characterization of carbon fiber composite materials for RF applications. In *Radar Sensor Technology XVIII*, Vol. 9077. International Society for Optics and Photonics, 907704.

[25] Valkyrie Savage, Xiaohan Zhang, and Björn Hartmann. 2012. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 579–588.

[26] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A fabrication pipeline to design and 3D print capacitive touch sensors for interactive objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 253–258.

[27] Robert F Stinson and Joseph A Sarro. 2002. The use of carbon fiber composites in sliding contacts. In *Electrical Contacts, 2002. Proceedings of the Forty-Eighth IEEE Holm Conference on*. IEEE, 175–183.

[28] Tatyana Vasilevitsky and Amit Zoran. 2016. Steel-sense: Integrating machine elements with sensors by additive manufacturing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 5731–5742.

[29] Shoukai Wang and DDL Chung. 2006. Self-sensing of flexural strain and damage in carbon fiber polymer-matrix composite by electrical resistance measurement. *Carbon* 44, 13 (2006), 2739–2751.

[30] Daniel Wigdor et al. 2015. Printem: Instant Printed Circuit Boards with Standard Office Printers & Inks. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 243–251.

[31] Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. 2012. Printed optics: 3D printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 589–598.

[32] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. BioLogic: natto cells as nanoactuators for shape changing interfaces. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 1–10.