3D Printing of Electro Mechanical Systems

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Abstract

Recent research has focused on the fabrication freedom of 3D printing to not only create conceptual models but final end-use products as well. By democratizing the manufacturing process, products will inevitably be fabricated locally and with unit-level customization. For 3D printed end-use products to be profoundly meaningful, the fabrication technologies will be required to enhance the structures with additional features such as electromechanical content. In the last decade, several research groups have reported embedding electronic components and electrical interconnect into 3D printed structures during process interruptions. However, to date there appears to be an absence of fabricated devices with electromechanical functionality in which moving parts with electronic control have been created within a single Additive Manufacturing (AM) build sequence. Moreover, previously reported 3D printed electronics were limited by the use of conductive inks, which serve as electrical interconnect and are commonly known for inadequate conductivity. This paper describes the fabrication of a high current (>1 amp) electromechanical device through a single hybrid AM build sequence using a uPrint Plus, a relatively low cost 3D. Additionally, a novel integrated process for embedding high performance conductors directly into the thermoplastic FDM substrate is demonstrated. By avoiding low conductivity inks, high power electromechanical applications are enabled such as 3D printed robotics, UAVs and biomedical devices.

***Index Terms—* Additive Manufacturing; 3D Printed Electronics; 3D Printed Electromechancial devices; hybrid manufacturing; Structural Electronics**

I. INTRODUCTION

Additive Manufacturing (AM) (more popularly referred to as 3D printing) is a form of manufacturing in which a Computer Aided Design (CAD) model is captured and then subsequently fabricated layer-by-layer. The AM technology used to create the electromechanical part described in this paper is a polymer extrusion-based process – in which a thermoplastic material is extruded through a heated nozzle to provide a robust polymer substrate – in the end fabricating an object that is customized without the requirement for tooling. Although the process is useful for fabricating mechanical parts such as custom fixtures or molds, the shapes are relegated to simple mechanical objects. Recent research has shifted focus into increasing the functionality of AM-fabricated parts through the integration of electronic components and interconnects into 3D printed devices [1-6]; however, reports of freeform fabricated electromechanical devices are limited. In [7], AM technology was used to build a simple electrostatic biocompatible actuator with a service life of two to three actuation cycles, this displays a clear interest in increasing functionality of AM parts. Concurrently to and independently of this work, a cleverly designed 3D printed stepper motor has surfaced in pop culture [8], but the fabricated parts required a final assembly process and could have been easily fabricated with traditional manufacturing. Consequently, the example does not take advantage of having access to individual layers during a build with AM and seems to offer no significant advantage in AM other than the reduction in amortizable cost of the initial units by eliminating expensive tooling. The University of Texas at El Paso (UTEP) is exploring the fabrication of fully electromechanical devices fabricated in a single build sequence that includes an AM technology with process interruptions allowing for the robotic placement of components (microcontrollers, magnets and other electronic control circuits) to create multi-functional 3D printed structures.

The advantages of a 3D printed electromechanical device such as a motor – fabricated in one single build sequence as opposed to an assembly process - is the ability to apply the benefits of 3D printing (unit level customization) to not just mechanical parts but also electronic and electromechanical parts within larger customized systems such as a robot or UAV. When each fabrication can be unit-level customized as required for the final application, the possibility exists to fabricate objects that conform to human anatomy or to provide rapid deployment of a specific UAV system. Other benefits include the ability to provide geometric complexity for free - fabricating structures that cannot be built in any other technology (e.g. internal cavities or meshes). Additionally, by adapting the placement and orientation of the electronics within the final envelope of the design, volumetric efficiency can be dramatically improved.

II. Previous Work

Recently, reports in literature describing 3D printing with embedded electronics have been growing. The combination of Direct Printing (DP) of conductive inks onto 3D printed structures was introduced by Palmer [9] and expanded in Medina [10] and Lopes [11] in which simple circuits were implemented to demonstrate functionality by integrating a dispensing system into a stereolithography (SL) machine using three-dimensional linear stages with a dispensing head. This approach included a demonstration of a simple prototype temperature sensor with nine components including a 555-timer chip. Navarrete [12] describes improvements to using DP on AM substrates by introducing channels into the substrate for the conductive material in order to provide delineation of the electrical lines and allow for the reduction of line width and spacing while simultaneously reducing the possibility of line-to-line shorting. Line pitch was thus determined by the precision of the SL fabrication (e.g. laser beam size) rather than the dispensing process with lower spatial resolution. 3D printed electronics can conform to any shape providing a unique advantage over mundane electrical systems and one example of exploiting the 3D design freedom is illustrated in a CubeSat called Trailblazer, which will be launched into low Earth orbit in late 2013. One of the elements of this small satellite is a 3D printed UV curable substrate with embedded electronics, including a microcontroller, gyroscope, crystal, and several passive components (e.g. capacitors and resistors) [13].

Though advancements regarding the process of DP electrical interconnects integrated into

3D printed structures were described and have contributed to the advancement of low power applications, such as magnetometers or six-sided gaming dice, the research to date described electronics that do not require electric currents exceeding 100mA. In these low power cases, the conductive ink interconnects are sufficient in terms of conductivity. However, the application described in this paper requires electric currents that can reach 5 amps and possibly higher, which required an appropriately sized or capable current carrying conductor. A patent pending process developed at UTEP in which solid metal conductors can be embedded into 3D printed thermoplastic structures provides electrical interconnect with sufficiently high current density capabilities for the presented demonstration [13] – similar to the conductivity provided by traditional Printed Circuit Boards (PCB).

III. Fabrication

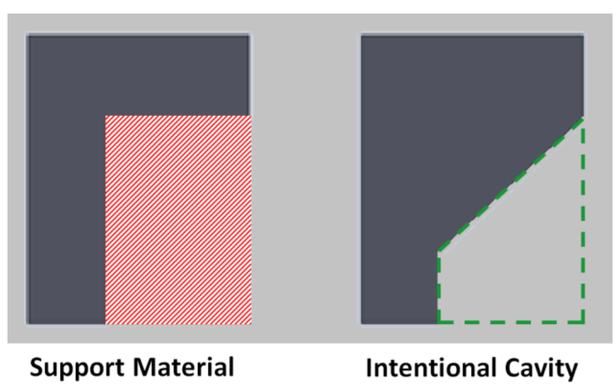
Although many AM technologies exists today that are capable of producing metal, ceramic or plastic substrates, an extrusion-based AM process that deposits thermoplastics was selected to create the 3-Phase DC motor due to ease of access to the build chamber, the low cost of operation, the durability of the thermoplastics and the simplicity of the build process. The goal of this line of research is to eventually allow consumers to download an electro-mechanical or electronic design from the internet (such as a cell phone or toy car) and 3D print a fully functional device in the comfort of their own home, or alternatively, to allow NASA to manufacture space hardware on the International Space Station or a lunar colony. Plastic extrusion AM uses commercial grade thermoplastics – providing for the fabrication of durable substrates. Additionally a sacrificial support material is used that can be removed in an ultrasonic bath to allow for overhanging substrate features. The AM machine selected to create the 3-Phase motor was a uPrint Plus manufactured by Stratasys (retail price of approximately $20k) and the material used was ABSplus - the material provided by Stratasys [14]. Consequently, this paper demonstrates that electromechanical devices can be fabricated with relative inexpensive printers and that printing multi-functionality is not limited to expensive commercial-grade AM systems. This capability is fertile for exploration and optimization by the Do It Yourself (DIY) community.

The main goal of this demonstration, however, is to illustrate the potential for multi-technology fabrication, which is currently under development at the W. M. Keck Center for 3D Innovation. Whereas the demonstration described in this paper was completed (1) with an inexpensive commercial system, and (2) with interruptions introduced for the manual insertion of components and electrical interconnects, the ultimate objective of this course of research is to fabricate a motor in a completely automated fashion with a novel multi-technology AM system (multi^{3D}). The demonstration illustrates what is possible to fabricate when multiple manufacturing techniques are integrated together. With contemporary AM providing the base fabrication process for a dielectric substrate, a comprehensive manufacturing suite is being integrated seamlessly to include 1) extrusion of a wide variety of robust thermoplastics/metals, 2) micromachining, 3) laser ablation, 4) embedding of wires and fine-pitch meshes submerged within the thermoplastics and 5) component placement. Collectively, the integrated technologies will be capable of fabricating *multi-material* structures through the integration of a wide variety of manufacturing systems (*multi-technology*) to provide *multi-functional* products (consumer wearable electronics, bio-medical devices, defense, space and energy systems, electromechanical devices etc.).

IV. Design and Build Process

The freedom of design provided by AM technologies allows a unique approach for conformal electromechanical devices. For example, the presented electric motor could be fabricated in the form of a conical shape if the intended use is in the nose of an airplane, or alternatively, mounting brackets could be designed onto the motor increasing the freedom of device placement within a large system on a case-by-case basis. This paper describes the process in which a 3-Phase brushless DC motor is constructed in a single build sequence, including a rotor inside a stator separated by two single row ball bearings that serve to maintain alignment between the two structures and allow the rotor to rotate freely within the stator. Designing electromechanical parts requires a more complex design representation using CAD when compared to a simple mechanical form, due to the concomitant mechanical and electronic features. These simultaneous features require both mechanical and electrical CAD methodologies and the confluence of both was completed manually in this example. Future work includes a unified methodology in which 3D printed electronics could be designed with a high degree of freedom component placement and routing within arbitrary forms.

The first complication faced when using a uPrint Plus was the lack of available options and control over the rastering and support material. This includes no option for at-will addition or removal of support in the design to be printed. Whereas in some AM system, the user has arbitrary control over the use of support, design rules had to be implemented in the uPrint design to avoid post-processing and other complications associated with the support material. Eliminating the need for support is important when building internal features since access for support removal may be difficult or impossible. In the case of the presented single motor build, moving internal structures and electronic components were encapsulated during the build process, and consequently, the support cannot be easily removed after fabrication. The removal process involves an ultrasonic bath, where the device is submerged and heated in water for several hours until all the sacrificial material has been dissolved. If water-soluble support material is required to enable internal overhanging structural features and is subsequently removed in an ultrasonic bath after fabrication, electronic components cannot be included in the substrate prior to this post-process step. The minimum angle to avoid the automatic placement of support in the uPrint Plus's software is 45 degrees as determined through trial and error with the tool. The electromechanical part has to be designed in a way that takes advantage of using a minimum angle of 45 degrees for overhangs in order to avoid required support structures as shown in Figures 1. The form in Figure 1a has an overhang that requires support material, while the shape in Figure 1b is more gradual and can be completed without support material. Removing the requirement for support material has the additional advantage of faster fabrication by reducing total deposition time as well as eliminating the requirement for changing between the two materials. For the motor described in



(a) (b)

Figure 1 – Design comparison (a) support needed (b) no

this paper, the only support material used was for the base of the motor.

An alternative approach is to use different STL file processing software (e.g. Insight) that allows for complete control over placement and removal of support material. Normally, the uPrint Plus's proprietary software automatically places support material to serve temporarily to form a cavity, but for design cases like the one described in this paper, where components are being embedded, the user can identify that the cavity will be filled with a component rather than maintain free space and that once embedded can double as support material. This allows for material to be dispensed over the component and subsequently continue the build. Direct control of deposition of the support material allows the user to evaluate each cavity and decide if a component is present and will act as support. The lack of additional control provided by the uPrint Plus software led to the implementation of 45 degrees to indirectly avoid support material and allow for cavities inside the device where components can be embedded.

A further complication of the 3-Phase motor is that this application requires high electric currents depending on performance and power requirements and was designed to be able to consume up to 10 amps at 12 volts; however similarly sized motors on the market can reach up to 120 amps or more. Initial versions of the UTEP AM motors have been fabricated using electrical interconnects dispensed using a Direct-Write (DW) method for conductive inks - typically consisting of a silver-based ink suspended in a binder. These types of printed interconnects have very low conductivity due to the restrictions imposed by the plastic substrate on the curing temperatures. Conductive inks generally cannot handle high current densities (>0.02mA/um^2) where 150 mA fused a printed line of approximately 250 um width and 10 um thickness – as opposed to 40 gauge wire at 1.5 mA/um^2 [15]. When used to connect the electronics and electromagnets of the motor, printed lines were destroyed due to high current densities required and became open circuits – resulting initially in unreliable operation and ultimately in system failure. Therefore the use of conductive inks was not possible. Alternatively, a patent pending process developed at UTEP was employed that embeds solid copper wire directly into thermoplastic substrates by submerging the wire through either ultrasonic welding or joule heating [13]. With 24 to 40 gauge embedded wires (511 microns to 79 microns in diameter, respectively), the current carrying capacity requirements were achieved (32A to 8A, respectively [15]), while simultaneously maintaining high routing densities with center-to-center distances as low as 150 microns. Figure 2 illustrates an 80 micron wire embedded into the thermoplastic substrate through ultrasonic embedding in a conceptual drawing and as a photo of an example fractal antenna.

A third challenge of building the motor included the insertion of electronics into partially fabricated structures during interruptions of the extrusion-based AM process - due to the maximum storage temperature of the components. Whereas a stereolithography process provides a build chamber at ambient temperature, the temperature involved in an extrusion system can be damaging to electronic components – particularly at the extruding tip, where temperatures are substantially higher than the rest of the build chamber. Using a thermocouple the tip temperature

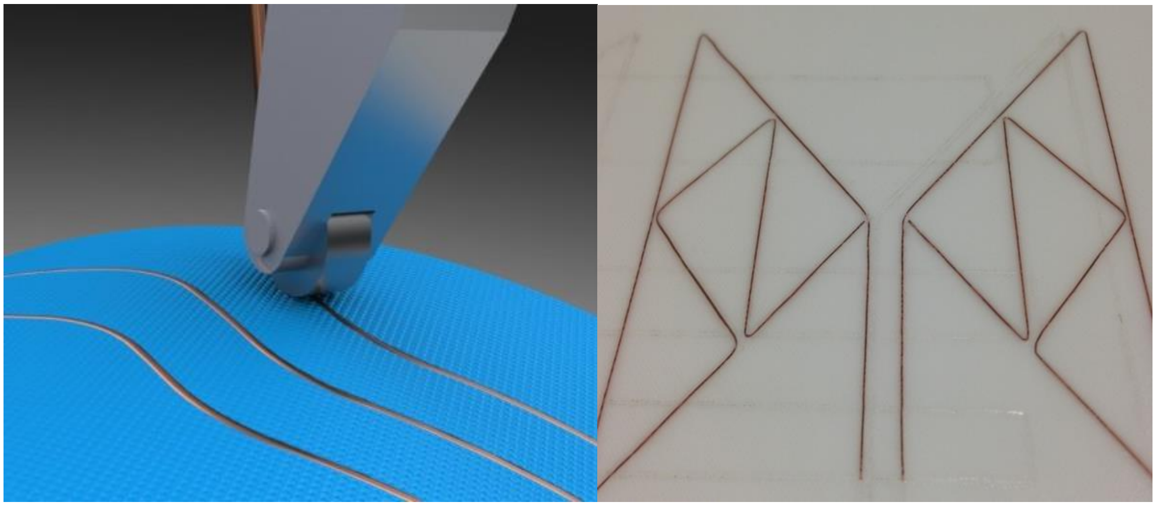
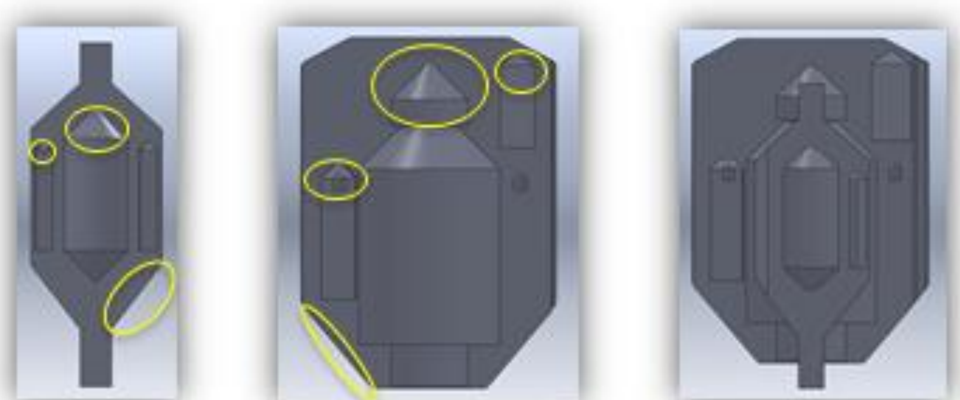


Figure 2 – Thermally embedded wire (a) conceptual depiction of embedding process and (b) in actual example in a 3D printed substrate (fractal antenna)

(while extruding) measured 200 degrees Celsius and the chamber temperature was 75 degrees Celsius. The temperature of the extruding tip is sufficient to destroy components - the majority of which have maximum storage temperatures of 150 degrees Celsius or lower. Further studies are necessary to understand the implications of these short durations of applied high temperatures to the functionality of the components. By applying the 45 degree rule, the two main fabrication issues are solved in the context of the uPrint Plus: (a) eliminating internal support material to maintain internal cavities and allow for moving internal structures, and also (b) minimizing the exposure of the components to the extruding tip. By designing 45-degree "roofs" over every fully enclosed cavity, no support material was necessary, the component becomes fully contained and the components temperatures are reduced. This 45-degree approach, illustrated in several locations of the motor in Figure 3, also has the added benefits of reduced weight in the final structure, material costs and fabrication time.



(a) (b) (c)

Figure 3 –CAD file (a) rotor (b) stator (c) full drawing, showing cavities with "roofs", highlighted in yellow are 45 degree features eliminating the use of sacrificial material

Additive manufacturing also provides the opportunity of adopting a more volumetrically efficient electromechanical part. In this application the electric motor occupied a total of six cubic inches of space, in which included six magnets, nine electromagnets, two ball bearings, and an electronic speed controller, for a total of 18 components. Each of these components where placed during five pauses within the build - separated into six fabrication segments. The total AM building time of the motor was seven hours and six minutes. Including the duration required for manually embedding components, an additional 39 minutes are required. The five process interrupts are shown in a schematic in Figure 4. The first pause was used to insert the first of two ball bearings to help reduce friction and to provide alignment between the two moving structures: the rotor and the stator. The second process pause was used to insert the magnets inside the cavities of the rotor. Then, the electromagnets were placed and electrically connected in the third process interrupt and treated as pre-manufactured components (similar to the chips and magnets) to avoid the complication of printing the coils within the structure. The fourth process interrupt was used to insert the second and final ball bearing that completed the two mechanical connections between the subsystems allowing the rotor to maintain concentric position within the stator in conjunction with the first ball bearing. The fifth and last process pause was used to embed the electronic speed controller and connect it to the electromagnets. The last segment encapsulates the electronic speed controller and completes the outer volume of the motor. Once the final segment was finished the motor was removed. The amount of sacrificial material used at the beginning of the build is 4% of the total material and was easily removed from the platform and also from the part. Immediately after fabrication, only power and a control signal were required for the motor to operate.

Electrical interconnects were completed (soldered by hand) during the third process pause in which nine electromagnets in Wye formation were connected to the electronic speed controller. The three-phase connection from the electromagnets was coupled to the electronic speed controller with enamel wire. Embedding enamel wire into the thermoplastic substrate during the third

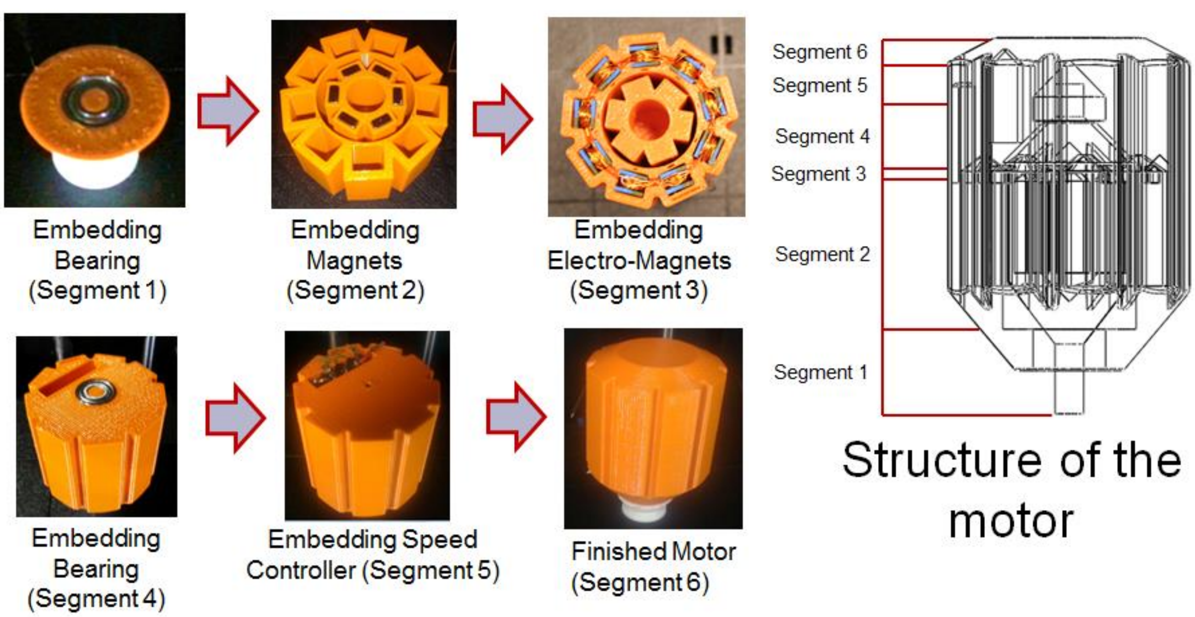


Figure 4 - Pauses in between the build

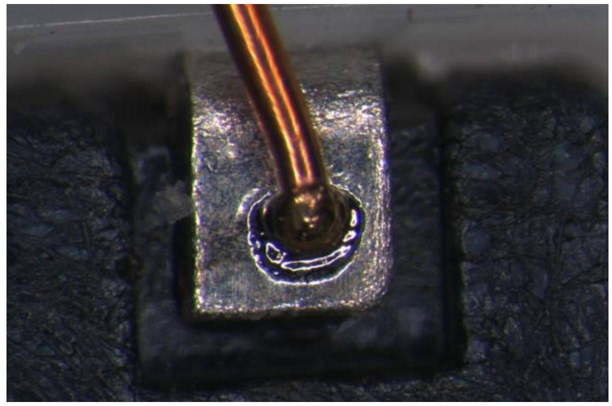


Figure 5 –Electromagnets embedded *Figure 6 – Micro-Welding with YAG laser*

process interrupt provided the additional benefit of maintaining the position of the components during subsequent fabrication. The enamel dielectric avoided shorts between lines as the wires shared a single channel in the substrate. These channels also provided a flush, planar surface to continue thermoplastic deposition as seen in Figure 5. Connections were then hand soldered on the final pause to the electronic speed controller completing the circuit. As described in Section 2, a system under development (multi^{3D}) will provide the automation of a range of integrated manufacturing technologies such as laser welding systems for a solderless and automated component connection solution. An example of a laser-welded component is shown Figure 6. Implementing a YAG laser micro-welding system from Miyachi Unitek [16] within a custom machine like the Multi^{3D} is the subject of ongoing work for the fully automated fabrication of

Figure 7 - Testing set-up

electronic and electromechanical devices.

V. Results

An electronic speed controller (ESC) is used to control the speed of the motor and requires power and a Pulse Width Modulated (PWM) control signal. A microcontroller or a function generator is used to create the PWM signal - the duty cycle of which is proportional to the speed of the motor. Connecting the 3-Phase printed motor to a 12 V power, supply and providing the control signal to the ESC is enough to be able to start and run the 3-Phase DC motor immediately after removal from the building platform. Comparing the 3D printed motor to a commercially-available off-the-shelf 3-Phase brushless DC motor allows for a comparison of how additive manufacturing can compete with traditional manufacturing. The evaluation consisted of comparing torque vs. time and RPM vs. time for an identical start up sequence of power and a PWM signal. To determine these values, a photodiode and laser system were used to measure the angular velocity and acceleration of the motor as shown in Figure 7. The calculated moment of inertia and measured angular acceleration were used to determine torque.

The initial angular acceleration on the 3D printed motor is slower than that of the commercial motor (Figure 8) however after approximately one second, the rate became comparable. The same relationship was seen between the torques of the two motors in Figure 9. Due to initial design constraints of the AM-fabricated device, the motors were different in the number of coils and magnets - with nine electromagnets and six magnets for the AM motor compared to 12 electromagnets and 14 magnets in the commercial motor. The difference in the number of magnets is the main culprit for the disparity in performance between the motors. The distance between the rotor and stator also played a role in the performance difference where the minimum separation allowed by the software was 1mm. Unfortunately, the difference in architecture does not allow for a direct comparison of the motors, but does provide a general non-

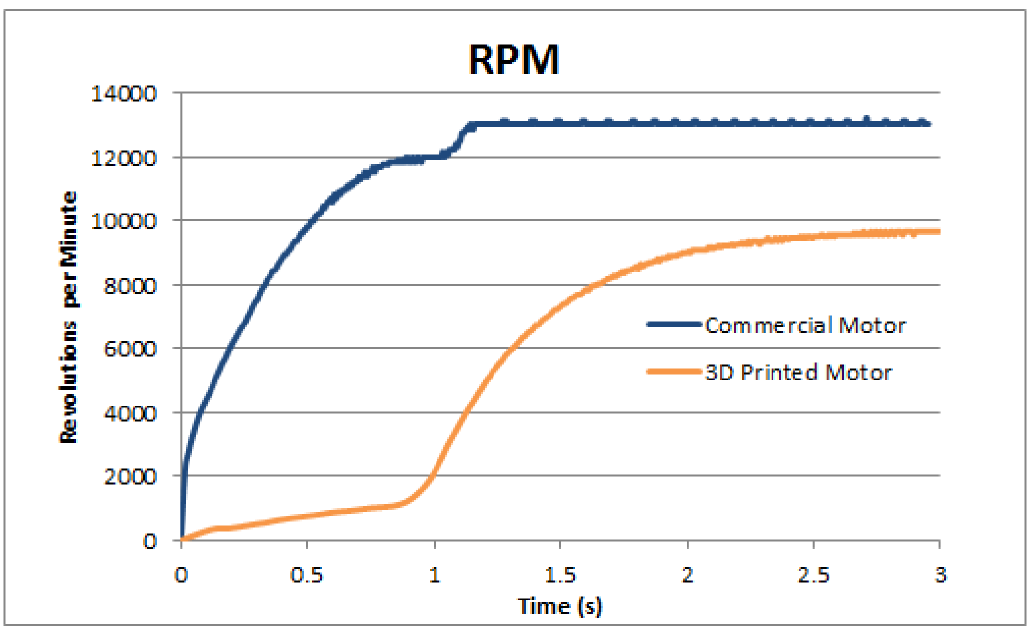


Figure 8 – RPM comparison

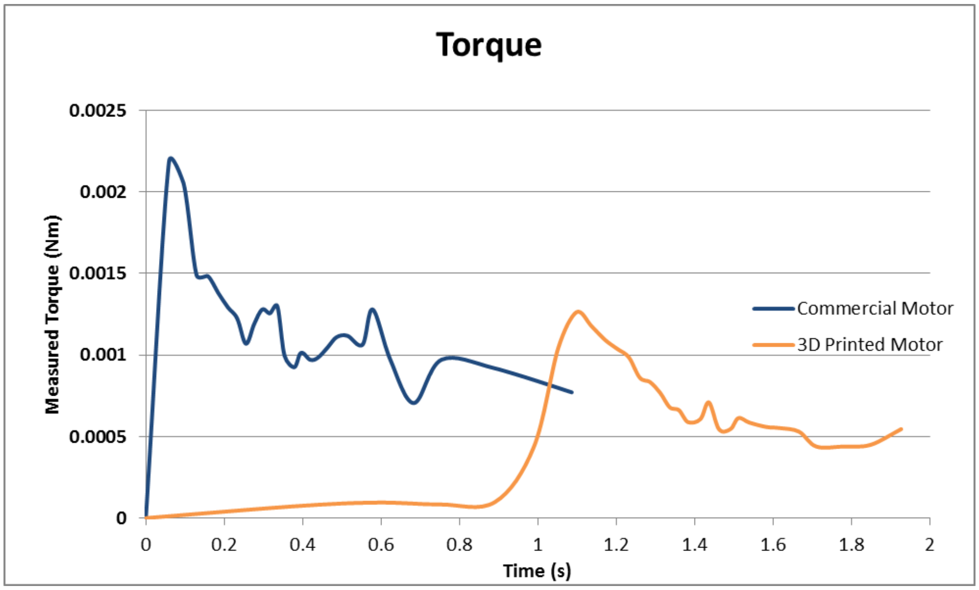


Figure 9 – Torque comparison

qualitative evaluation. Future work includes fabricating a motor that is identical to a commercial system at least in terms of number of internal components for a more direct comparison.

VI. Conclusion/Future Work

An electromechanical device was fabricated with 3D printing and functionality was demonstrated. Using relatively inexpensive commercially available equipment, printing of electronic and electromechanical devices is possible in remote places such as space or battlefields where no readily available inventory is in stock – or by the DIY community. Inevitably, even consumers will be able to download printable design files representing an electronic device, and subsequently, 3D print the device within their own home.

Though manual intervention was used in this example to build an electromechanical device, this system demonstrated the potential of what can be fabricated with a multi-material and multi-technology 3D printer. Current work includes seamlessly integrating several manufacturing technologies into a single system ($Multi^{3D}$) including multiple polymer extrusion technologies, micro-machining, wire embedding, pick and place and micro-welding. Once complete, electromechanical systems such as the demonstration piece described in this paper will be fabricated in a single build sequence without manual intervention. Eliminating human involvement will allow for improved manufacturing tolerances and simplicity of fabrication and eventually will enable a "press print" methodology where one can start a fabrication of a CAD design and return to a new functional device the next morning.

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