DEVELOPING TECHNIQUES TO 3D PRINT ELECTRIC MOTORS

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ABSTRACT

In this paper, we present a new approach for the establishment of a self-replicating machine. One of the most critical components to building a self-replicating machine is electric motors. While 3D printing (additive manufacturing) is well established in the context of self-replicating machines (such as RepRap), it has been deployed in 3D printing structures rather than motors. This paper will present progress in developing 3D printing of an electric motor. The final objective is to build a self-assembled electrical motor by 3D printing. The application of the self-assembled 3D printed electric motor is as the core component of a self-replicating machine[1]. After deployment on the Moon, such a machine can be used as a lunar robotic system to utilize lunar materials to build copies of itself as well as a wide range of future space assets such as lunar base, solar power satellites, lunar mines, etc. If we can build such a machine, we can overcome the slow pace of technological development in space exploration while accomplishing a sustainable method of space exploration at low cost. In this paper, several prototypes of electric motors were fabricated and tested to demonstrate the possibility of 3D printing a fully electric motor. If fully achieved, it will demonstrate that 3D printing could lead into sustainability in space exploration.

1 INTRODUCTION

Additive Manufacturing (AM) is a form of manufacturing in which a Computer Aided Design (CAD) model created and then fabricated layer-by-layer. 3D printing contributes to developing many industries such as the automotive and aerospace industries. The benefit includes cutting down costs and allowing for much faster development and testing of products with much more complex structure when compared with traditional manufacturing processes such as casting or machining. Although the process is useful for rapid prototyping, the shapes are limited to simple mechanical objects. Recent research has changed focus into increasing the capability of using AM to fabricate parts with the integration of electronic components[1][2][3][4][5]. However, previous studies of fabricated electromechanical devices are still limited. The AM technology used to create the motors prototypes in this paper is Fused Filament Fabrication (FFF), this technique can manufacture highly complex components using a polymer extruder in which a thermoplastic material is extruded through a heated nozzle to produce the final part without the requirement for tooling. This paper discusses the different techniques that used to achieve the 3D printed electric motors from a different perspective.

2 MANUFACTURING PROCESS

An electric motor mainly consists of a rotor and a stator, both rotor and stator are separated by an air gap. The rotor is the rotating part of the motor which carries the windings. While the stator is the stationary section of the motor which holds the permanent magnets. The rotor is usually made by using Silicon Steel which is provided as thin lamination sheets. The lamination sheets are cut by laser to form the desired patterns. These sheets are fixed together to form the final shape of the rotor cores[6][7][8]. In this paper, brushed DC motor (BDC) were selected to be studied and to be 3D printed. Since the electric power source in classical BDC motor is connected directly to the rotor winding through a commutator and brushes. Therefore, the need of using electronic commutation that based on hall position sensors is eliminated [6]. In this study, different approaches were used to achieve a fully 3D printed motors. Most of the work was done by using RepRap machine, this machine can manufacture approximately half of its own parts. The RepRap is consisting of a combination of printed mechanical components, stepper motors, extrusion, and a hot-end for melting and depositing sequential layers of polymers. It is controlled by an open-source micro-controller Melzi V2.0. The extruder intakes a filament of the working material such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) melts it and then extrudes it through a nozzle to form the desired shape. This printer has a building volume of 210 mm (W) x 190 mm (D) x 140 mm (H) with a building speed of 1,800 mm/min. The RepRap has a 0.5mm nozzle size, positioning accuracy of 0.1mm and a resolution of 0.0125 mm. All 3D models were created using PTC Creo CAD software, the files were converted into STL format. Pronterface is the communication software which is used to talk to the RepRap Pro machine using a format which the printer understands. This known as a G-code file. Before a model can be processed a slicing tool is needed. Slic3r software is being used for this task, it took the solid model file (STL format) and sliced it into layers[9].

2.3 Approach I

The first approach is focusing on 3D printing and testing only the rotor of the BDC motor and keep the conventional stator (i.e. permanent magnets). The 3D printed rotor core shown in Fig.1a was 3D printed using Magnetic Iron ABS filament by the RepRap, eight of equally spaced slots were created at the outer circumference of the rotor core. These slots are used for winding the copper coil, for simplicity only four poles were winded with copper coil 30 MAG (0.16 mm diameter), the number of turns per each pole was 95 turns. The commutator was also 3D printed using ABS filament, four sets of contact copper sheet (0.01") were attached to the commutator. Both the rotor core and the commutator were attached to steel axel of 3.175 mm diameter and 20 mm length, the ends of the winded coils were soldered by hand to the commutator copper tapes so that an electric power source is connected to the rotor winding through a commutator and brushes, and thus the two stationary brushes come into contact with the copper conductor tapes of the commutator in order to reverse the flow of current in the rotor. Two of copper wires 20 GA were used to form the brushes. Moreover, the same above procedure was repeated to create another two rotors constructed from silicon steel particles (Fe-Si) with two different composition Fe-3Si and Fe-6.5Si, Fe-Si (electric steel) is the most widely used soft magnetic in building electric motors due to its high permeability [10]. The two Fe-Si cores were printed by using cold spray additive manufacturing technique[11], and they were provided by National Research Council Canada (NRC) Quebec, the diameter of each core was 40 mm with height of 14 mm, they were covered with two 3D printed thin disks, PLA filament was used to print these disks in order to create the needed slots at the outer circumference of the core. Only four of these slots were used for winding the copper coil with the same numbers of turns that were used in the first rotor Fig.1b and 1c, this allows for better comparison among them, the test of the two 3D printed motors were successful.

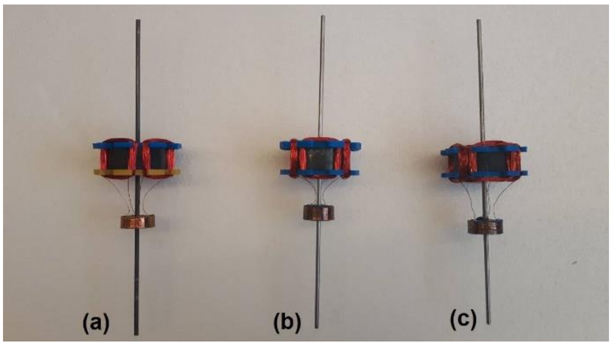

Figure 1: DC electric motor rotor
(a) Magnetic Iron (b) Fe-3Si (c) Fe-6.5Si

2.3 Approach II

A study was carried out to investigate the possibility of eliminating the permanent magnets, self-excited DC motors principles were chosen for this purpose, this is because electromagnetic induction is used in this kind of motors to replace the permanent magnets. The working principals of this type of motors are that the rotor and stator winding are connected in parallel. Consequently, the current in the stator and rotor windings are independent of one another Fig. 2.

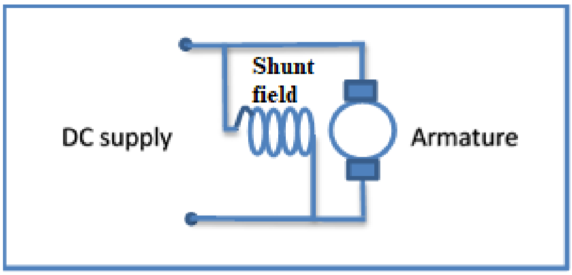

Figure 2: Self-excited shunt DC motor.

To apply the same principle, the four permanent magnets of the classical DC motor were replaced by four soft iron Fe 99,9 % roads of 12.7 mm diameter and 35 mm long. This type of material has the features of radially magnetized, fast demagnetization, and can create a concentrated field that is as much as 50,000 times more intense than an air core. The four poles were winded with copper coil 30 MAG (0.16 mm diameter), winding was done on a mini lathe machine. To have the same number of winding, the outer diameter created to be the same for all poles (Around 32mm in diameter). The four poles were glued on L shaped steel brackets Fig. 3. Although the poles were not 3D printed they can be fabricated using selective laser sintering (SLS)[12].

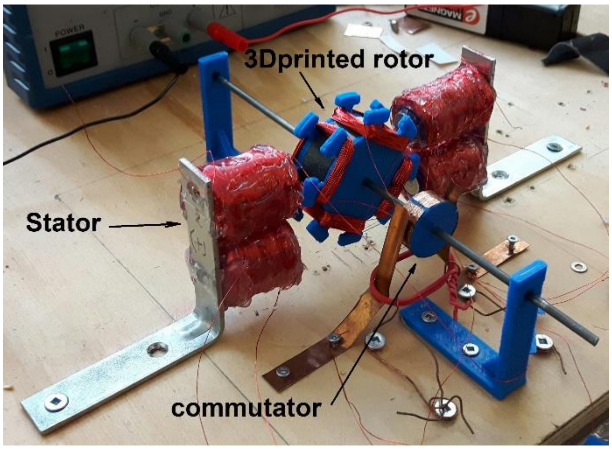

Figure 3: 3D printed Self-excited shunt DC motor.

2.3 Approach III

The study conducted in this approach was to eliminate the use of copper winding on the rotor motor, to attain this approach axial-flux motors (pancake motors) were selected. This type of motors may have more than one rotor. The structure of Pancake DC brush motors is similar to the conventional motor apart from its shape and size, where pancake motors are more compact due to its thin rotor. Similarly, this kind of motor consists of a rotor, commutator, stator, permanent magnets (PM) and winding[6][13][14]. This type was chosen due to the ability to print the winding on both sides of the rotor disks. The building process is planned to be done in two steps, the first step was to build and test an axial flux motor using copper coil winding and the second step was to replace the copper wire and rotor core with a PC board. The three parts rotor, commutator, and stator of the first prototype were 3D printed using ABS filament as can be seen from the Fig. 4. The rotor is contracted as a single-sided rotor with four slots that forming a four pole, each pole was winded with 95 turns of copper coil 30 MAG (0.16 mm diameter). The commutator was divided into four segments, each segment attached to a copper conductor tape and soldered by hand to the end of every winded coil. The motor was connected to 6V DC power so that the electricity flew through the two stationary brushes which are contacted with the copper conductor tapes of the commutator in order to reverse the flow of current in the rotor. A rotating magnetic field was generated according to the stator windings direction, the rotor aligns itself with the magnetic field of the two different poles of the permanent magnets, this leads to the movements of the rotor successfully.

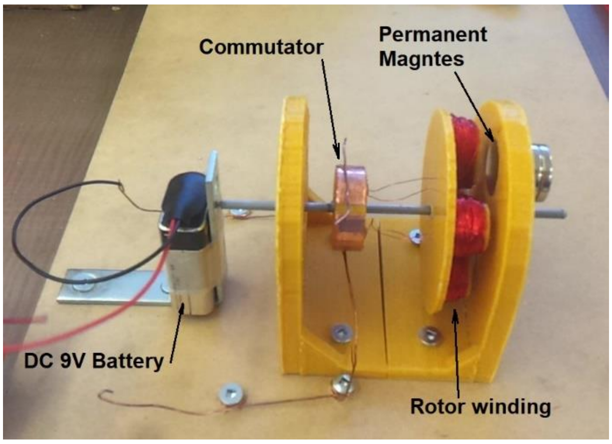

Figure 4: 3D printed DC brushed Pancake motor.

The second prototype was to build the rotor without using the copper wire technique in favor of reducing the complexity of 3D printing the winding wires. Printed circuit motor has been selected for this purpose due to its probability to be 3D printed, this is because winding in this type of motors are etched on printed board, this type of motors is used for many applications. It is an axial field DC. motor, the axial magnetic field is also provided by a set of permanent magnets arranged on the side of the printed disc. The first prototype was fabricated using rectangularly shaped winding disc type. A copper clade single sided PC board with a thickness of 1.6 mm and diameter of 70 mm was used to create the first armature winding as seen in Fig. 5, the thickness of the winding trace is 1.02 mm, and the clearance between traces is approximately 1 mm. The manufacturing process of this rotor was done by using the same idea of producing PC boards. The process of prototyping single-sided and double-sided circuits was conducted according to the following steps (1) Express PCB program was used to create the artwork for both single and double layer boards, the PCB schematic drawing then produced by a 600-dpi laser printer on a transparency film 416-T, (2) exposure kit 416-X from MG Chemicals was used with pre-sensitized boards. The pre-sensitized boards were exposed to UV light for about 10 minutes from distance of 5 inches, (3) the development process was used to removes any photoresist which was exposed to UV light. The process was done by immersing the board into one part of M.G. Developer (Cat. No. 418) with ten parts of water. The exposed resist was removed from the board after one to two minutes, the only resist remained was covering the schematic of the circuit, and (4) board Etching Process was done by using etching kit (Cat. No.416-ES) and Ferric Chloride etchant (Cat No. 415) from MG Chemicals. This process includes immersing the board in the ferric chloride where the air bubbles created by the etching kit helps to remove the unwanted copper[15]. Testing of this motor with an air gap of approximately 2mm showed that the rotor produced a very limited electromagnetic force that can't either attract or repel the permanent magnets, this is due to space limitation of the rotor where only five turns were printed in a single-sided board.

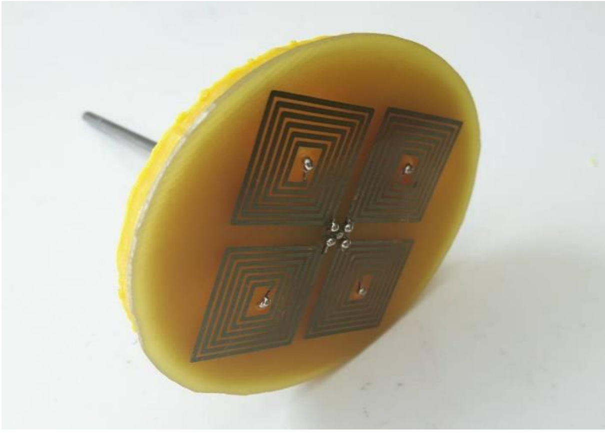

Figure 5: PCB rotor (Rectangularly shaped winding)

To overcome this issue a copper clade double-sided PC board with a thickness of 1.6 mm and diameter of 150 mm was used to create the armature winding as seen in Fig.6. the reason for using the double-sided board and doubling the diameter of the rotor is to increase the number of turns by increasing the winding space and having them on two sides. Moreover, the rectangularly shaped winding was replaced with an invented octagon shaped winding to increase the number of turns which will lead to the increase in the produced electromagnetic force. This case allows us to have 9 turns per winding side and 18 turns in total, the thickness of the winding trace is also 1.02 mm, and the clearance between traces is approximately 1 mm. Testing of this motor showed that the rotor produces enough electromagnetic force to run the motor. Accordingly, another motor was fabricated with the same above procedures aiming to increase the number of winding, this was done by having two duple-sided PC boards connected to each other and separated by 3D printed thin layers.

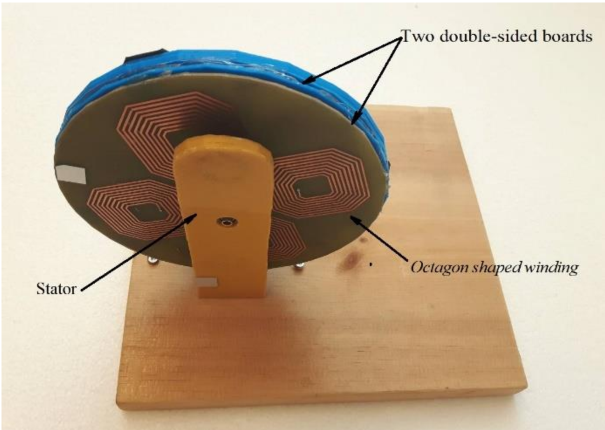

Figure 6: PCB rotor (octagon shaped winding)

3 RESULTS

The three motors in the first approach were connected to 15V DC power, the stator windings were consecutively energized, a rotating magnetic field was generated, the rotor aligns itself with the magnetic field of the two different poles of the permanent magnets which leads to the rotation of the three rotors successfully. The evaluation consisted of comparing RPM vs. time and Torque vs RPM. Testing was done by electric motor dyno Fig.7, this is a universal motor dynamometer (dyno) that measures the rpm, voltage, current draw, power and torque output of electric motors. The setup of the motors was modified to be compatible with test base of the dyno.

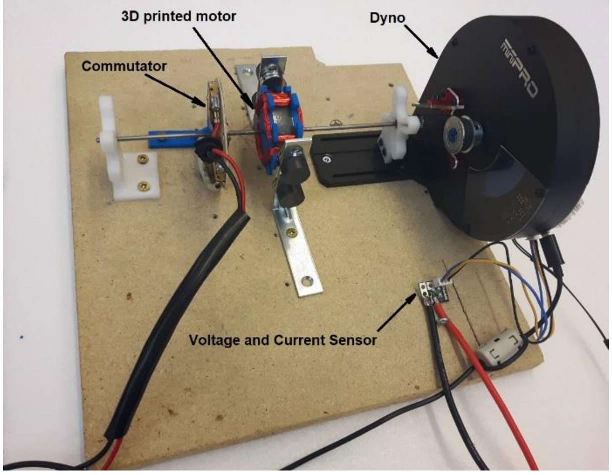

Figure 7: 3D printed DC motor connected to electric motor dyno

The angular velocity on the 3D printed motor fabricated by Magnetic iron PLA is higher than that of the two other motors which were fabricated using Fe-Si Fig. 8, however, the speed of the Fe-6.5Si motor is very comparable. The same relationship was seen between the torques of the three motors in Fig. 9. The difference in the architecture of the 3D printed motors compared to off-the-shelf motors does not allow for a direct comparison. Therefore, future work includes constructing a motor that is identical to a commercial system in terms of the number of poles, permanent magnets and winding turn for a more direct comparison.

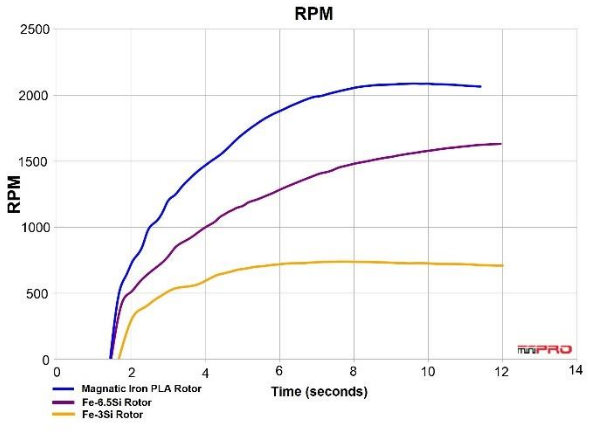

Figure 8: RPM Comparison

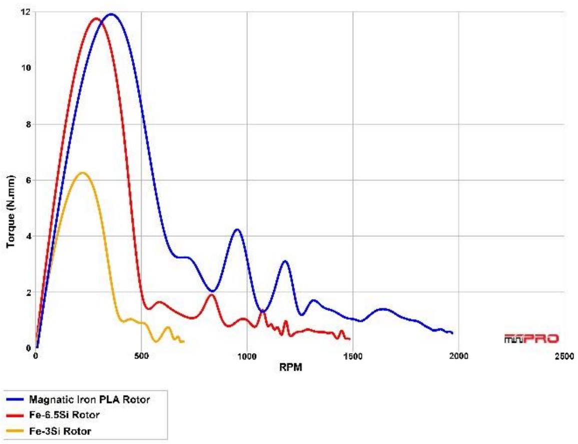

Figure 9: Torque Comparison

On the other hand, the Self-excited DC shunt motor which was fabricated in the second approach was connected to 17.8V DC power, Arduino electromagnetic field (EMF) detector was used to measure the produced electromagnetic field with an air gap equal to 5 mm, the result showed that each pole produced 23 gauss, this was enough to run the motor successfully. Furthermore, the results of building PCB Pancake motors showed that the single disk rotor produced enough electromagnetic force that's able to attract or repel the permanent magnets, allowing the motor rotating with a speed of 500 RPM when it was connected to 12V DC power, whereas the double disk rotor showed a slight increase in the speed to up to 700 RPM under the same conditions (i.e. the same voltage). The above results demonstrated that 3D print electric motor can be achieved by using different techniques.

4 CONCLUSION

Most of the parts of the radial and axial flux DC electric motors were fabricated with 3D printing, and the functionality was demonstrated with promising results. Using inexpensive commercially available equipment, fully 3D printed motors are also possible. Though manual intervention was used in these samples to build the electric motors, these systems demonstrated the potential of what can be fabricated with a multi-material and multi-technology 3D printer. Current work is in progress includes integrating several manufacturing technologies into a single system including multiple metals and polymer extrusion technologies, machining, copper wire extrusion, and soldering. Once completed, the electric motors which described in this paper will be fabricated in a single machine without human involvement which is the essential factor for space exploration. In addition to that, we are also examining the possibility of 3D printing a servo-disk motor. This is a DC brushed axial flux motor that has a unique structure, the armature is created from several layers of copper conductors etched on a flat disk. Brushes have a direct contact with the front-end connections of the armature windings which will give the advantage of eliminating the use of commutators [16]. Moreover, the investigation of 3D printing permanent magnets using a universal extruder and or Selective Laser Melting technique (SLM) is currently in progress too. Ultimately, if printed electric motors fully achieved, it will demonstrate that 3D printing could overcome the slow pace of technological development in space exploration while accomplishing a sustainable method of space exploration at low cost.

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