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Reviewed Paper

An automated vat photopolymerization process for composite parts with multiple spatially steered continuous fibers using a solenoid array grid

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Abstract

Fiber-reinforced polymer composite parts with continuous fibers embedded along bespoke spatial paths for a specific mechanical loading are shown to have superior stiffness and strength. We had presented a vat photopolymerization-based machine that can steer a single fiber along a spatial path within the layer-by-layer process. Here, we report an advancement that automates simultaneous spatial steering of multiple fibers. For this, we use permanent magnets that hold and steer the fibers in different directions with actuation provided by a cylindrical array of electromagnets. The method, machine, and process of actuating electromagnets along with the 3D-printed composite parts are presented.

1. Introduction

Additive Manufacturing of fiber-reinforced polymer composites with continuous fiber in specific paths is an emerging field of research due to the significant enhancement in strength and stiffness response with few fibers [1,2]. Laying continuous fibers in bespoke paths has predominantly been on planar [3-7] and curved surface [8-11] with one attempt in concurrently embedding fibers in spatial paths inside matrix [2,10]. In Khatua et al. [2], a significant increase in stiffness and strength could be seen by embedding a few continuous fibers (volume fraction < 0.5%) in paths specific for the loads on a bracket taken as example in the work. This novel system and process described in [2] uses a serial robotic manipulator in a vat photopolymerization process that embeds single fiber and for a composite part with multiple fibers inside matrix are realized as concatenation of mosaics, where each mosaic has only one fiber actively steered using the robotic manipulator. However, concatenation of parts to form a whole part in a vat photopolymerization process may introduce stress concentration points due to gaps or holes arising from shadows projected by other mosaics. It is essential for such an envisioned process to have a robotic system that concurrently embeds and simultaneously steer multiple fibers as the whole part is built layer upon layer. For example, thin-walled-axisymmetric parts like a cylinder with multiple fibers embedded in non-trivial paths for processes such as robotic filament winding can be realized in such systems.

In this paper, we present a design and development of a scalable robotic system consisting of a platform of solenoid coils arranged as a grid to move permanent magnets. These permanent magnets hold and steer multiple fibers as the part is built, overcoming the limitation of actively steering only one fiber using a robot arm in [2]. Such systems are envisioned to be scalable with thousands of solenoid coils to move as many as 15 permanent magnets on them.

2. Design of Array of Iron-core Solenoids

An iron-core solenoid is a tightly wound coil of conductor carrying current I inside it around an iron core. Due to the current in the coil, there is magnetic induction B_i inside the solenoid core and B_o outside the solenoid. An iron core increases the magnetic permeability inside the solenoid and thus increases the magnetic induction outside the solenoid B_o which is responsible for pulling ferromagnets and permanent magnets to proximity of the solenoid. The relationship of magnetization and magnetic field is expressed as follows:

$$M = f(H)$$

$$B_i = \mu_0(H + M)$$

$$H = \frac{\mu}{\mu_o} B_i$$

$$B_o = \mu_0 H$$

where H is the auxiliary magnetic field, M is a non-linear function of H for the iron core, and μ_o and μ are the vacuum and material magnetic field permeability respectively. Due to the presence of an iron core the magnetic induction B_i increases thereby increasing the magnetic field H. Increase in H increases the magnetization of the iron-core which in turn increases B_i until H saturates due to presence of the core. Since M and H have reached a saturation and B_o which is a function of H becomes greater than that of an air-core solenoid. Hence, in this work, iron-core solenoids were chosen over air-core solenoids [12].

Many such iron-core solenoids are arranged on a surface with the end of the solenoid facing the surface. This forms a grid of solenoids like a platform. The solenoid platform is designed to actuate coils by changing the magnitude of the current following through each coil controlled by a PWM. We want the platform and robotic system to be scalable. Hence, the entire platform was designed as multiple extendable modules with each consisting of a set of eight coils with the electronics for actuation mounted on the module. These modules are made to be extendable by using shift register HC595 ICs in series to form a long array of modules. HC595 is a Serial-In-Parallel-Out type shift register with one input and 8 outputs independently and simultaneously controlled using a latch pin integrated in the IC. Each module can have a maximum of eight coils.

We make a serial chain of such ICs and connect them all. A stack of such shift registers is thus made, meaning, the first byte (8 bits) sent into the serial must reach the end of the serial chain by shifting the byte to the adjacent shift register one by one by pushing a new incoming byte. For example, a chain of 10 shift registers in series require 10 such bytes and the last shift register's byte is sent first, and then subsequent bytes follow through the serial in a stacking sequence. Once the correct order of the bytes is stored in the shift registers, the latches are opened, and the output of the shift registers actuates a transistor switch connected to each coil. To reset the set of coils, a sequence of 10 zeros as a byte can be sent or the reset clock pin of the IC can be used. This sequence of sending bytes and activating the latches can be completed in microseconds and thus a PWM signal can be achieved. A PWM signal will actuate the coils with a reduced current as per the duty cycle. Figure 1a shows an illustration of the working of HC595, 1b shows the schematic of the circuit, and 1c shows the printed circuit board assembly with eight module (64 coils) stacks developed in this work.

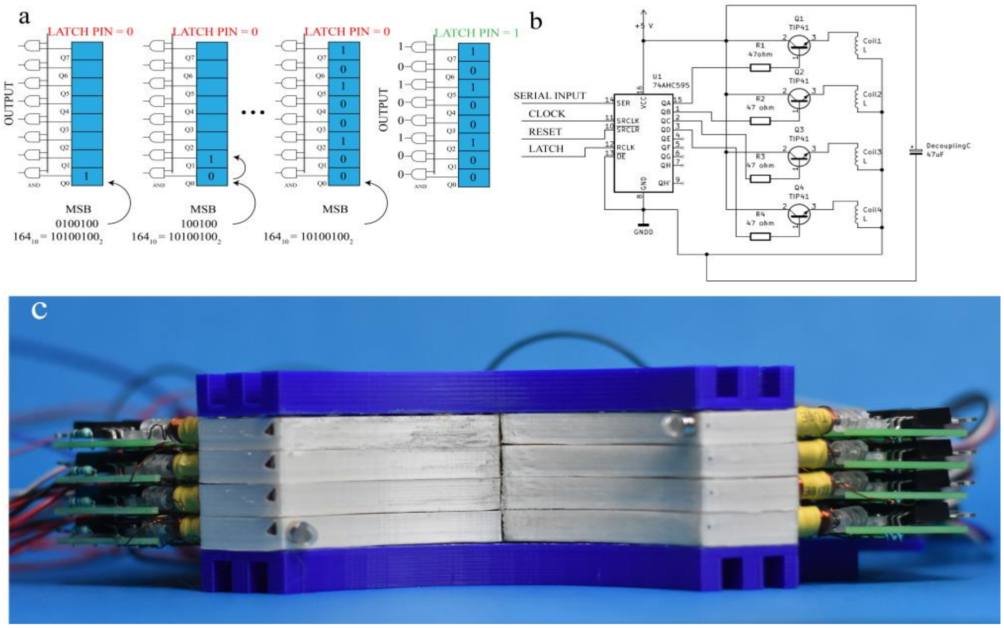

Figure 1: a. Illustration of a shift register IC. A shift register IC has 8 shift registers inside of it and each bit is shifted to the adjacent by an incoming bit. b. Circuit schematic of each module, only four outputs are shown with high side transistor as a switch, whereas in the present work, the transistors are connected at the low side. c. 64 coils arranged in a 4x2 grid of modules each consisting of 8 coils.

3. Process and Method

3.1 Vat photopolymerization setup and Materials

We use a vat photopolymerization setup developed in-house and used in [11] to augment the machine for the robotic system developed in this work. ANYCUBIC – Clear resin is used in this work as the matrix material and Toray-3000 carbon fiber tow is used as the reinforcement material. Figure 1a shows the setup used in [11] and 1b and 1c shows the added solenoid platform to the existing setup. The fibers were gradually embedded across multiple layers in a predefined curve by tracing the tangents of the curve as the part is built. The robot holds a single fiber taut using the end-effector attached to the robot. The system in [11] can actively steer and embed one fiber in a part. The system in this work can simultaneously steer multiple fibers in a single build.

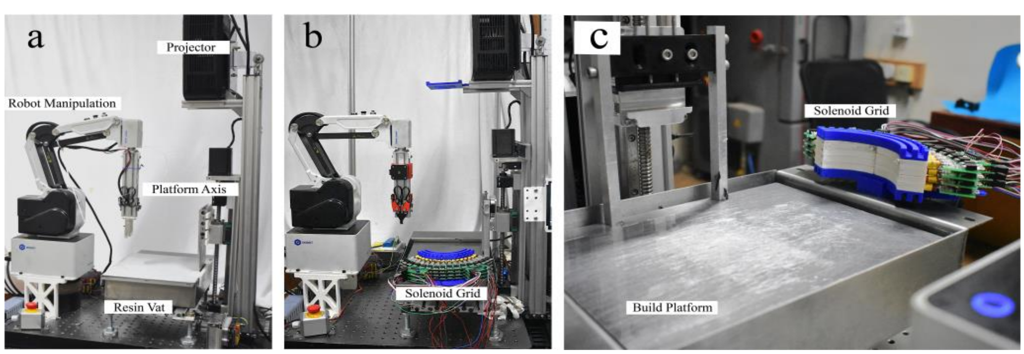

Figure 2: a. The vat photopolymerization machine is used in [11], b. Same setup addended with the solenoid grind developed in this work. c. An alternate view of the setup.

3.2 Steering of Fibers using Permanent Magnets

In the present work, permanent magnets are moved across a multi-solenoid platform by actuating a set of solenoids. The magnets are attached with a hook that allows fibers to be held loosely and when a solenoid is activated these magnets move to the top of the active solenoids. This way the fibers are steered as the part is built layer upon layer in the VPP process. A designated path for a magnet is decided prior to the fiber embedding process and it is fed to the robotic system as a series of images. The logic of the images fed to the system is explained in the Section 3.3. The continuous fibers are simultaneously embedded in the part with fibers spanning across multiple layers. Figure 3 shows an illustration of the envisioned system.

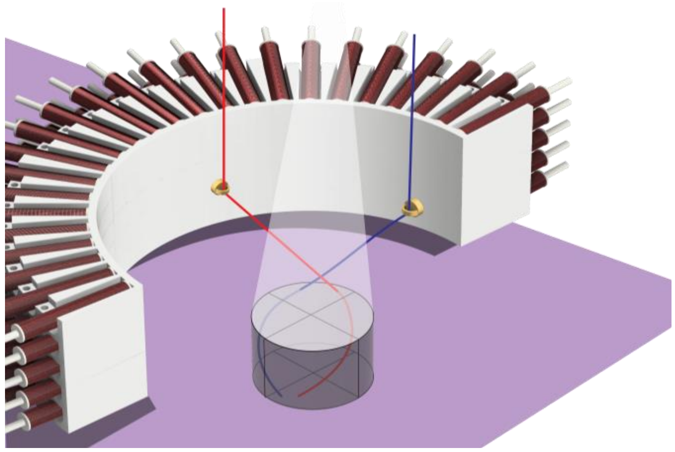

Figure 3: The illustrated robotic platform, where yellow hooks are the magnets that steer fibers (annotated in red and blue) as the part (off-white) is built layer-by-layer in a VPP process

3.3 Process of moving a permanent magnet in a path

The platform is an array of modules each with eight solenoids that are connected in a series configuration for this work. This series of modules can be arranged into a set of rows and columns much like a bit-map image. Each pixel of the bit-map image is a signal for the corresponding solenoid. It is convenient for us to convert these images into a stack of bytes and then pass it on into the serial chain. A pre-determined path is made as a series of images with two white pixels in each image indicating that at most two coils are active in each instance. The location of white pixel changes according to the paths desired. Figure 4 shows the process planning for the current robotic system where an image is converted into a stack of bytes.

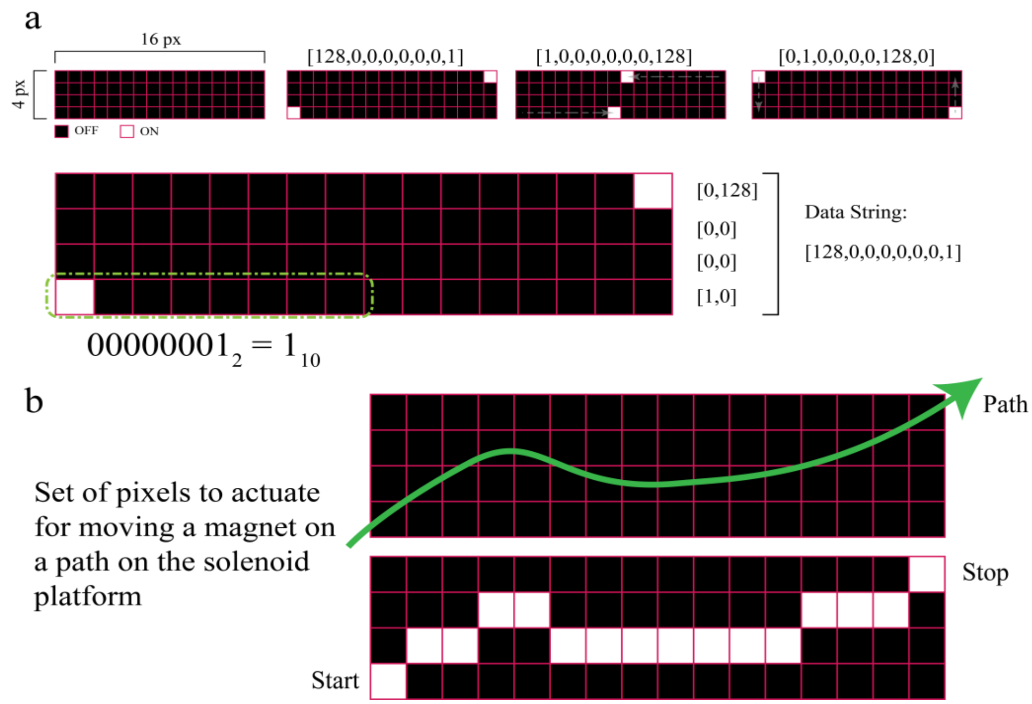

Figure 4:a. Logic of converting an image into a serial string of bytes that is sent by a serial to the robotic system. A white pixel on the image means an ON state and black is analogous to that of an OFF state. The addressing of the coils is from left to right in the modules with the left most coil bearing the least significant bit. b. An illustrated path is converted into a set of pixels and each of the white pixel is converted into a string, individually and is sent to the system from the start of the path to the end.

4. Results

Single module actuation: A series of coils are switched ON and OFF with a time interval of 10 milliseconds at OFF state. This delay is essential for the decay of the field due to the ferromagnetic core. Without a transition through OFF state, the current system cannot move the permanent magnet. Figure 5 shows a permanent magnet swinging across the eight coils.

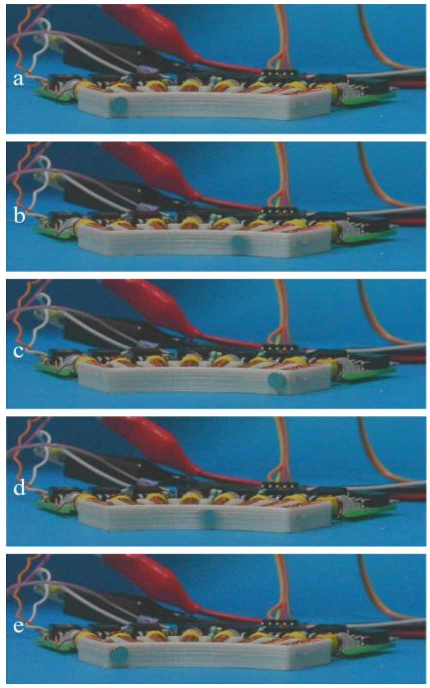

Figure 5: A single magnet is moved across one module consisting of 8 coils. a-e shows the movement of the magnet back and forth across the module's surface.

Actuating a stack of modules: A stack of eight modules used in this work is a 4x2 arrangement of modules whereas the data connection is a row wise serial connection starting from the bottom row. The output of the last module is not connected. One can connect the output to probe the data sent through the serial. Figure 6 shows two permanent magnets maneuvering across the 64-coil grid. A similar technique as single module actuation is used to actuate the coils, the sequence of data is sent first, and the common latch is excited to simultaneously actuate the desired coils.

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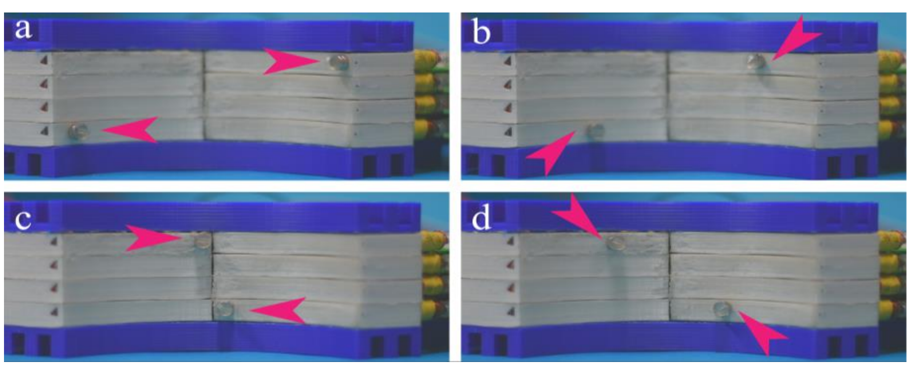

Figure 6: Two magnets moving across a grid of 64 coils. The coils are actuated in manner as described in Section 3.3; two magnets (highlighted by pink arrows) move from side to side as shown in images from a-d.

3D printed fiber-reinforced parts: A part with multiple spatial fibers simultaneously embedded is shown in frame-by-frame picture in Figure 7. The two fiber paths start from the first layer of the print, where these are manually attached to the build platform and are gradually steered by the solenoid grid till the end of fiber path. The finished part is shown in Figure 8.

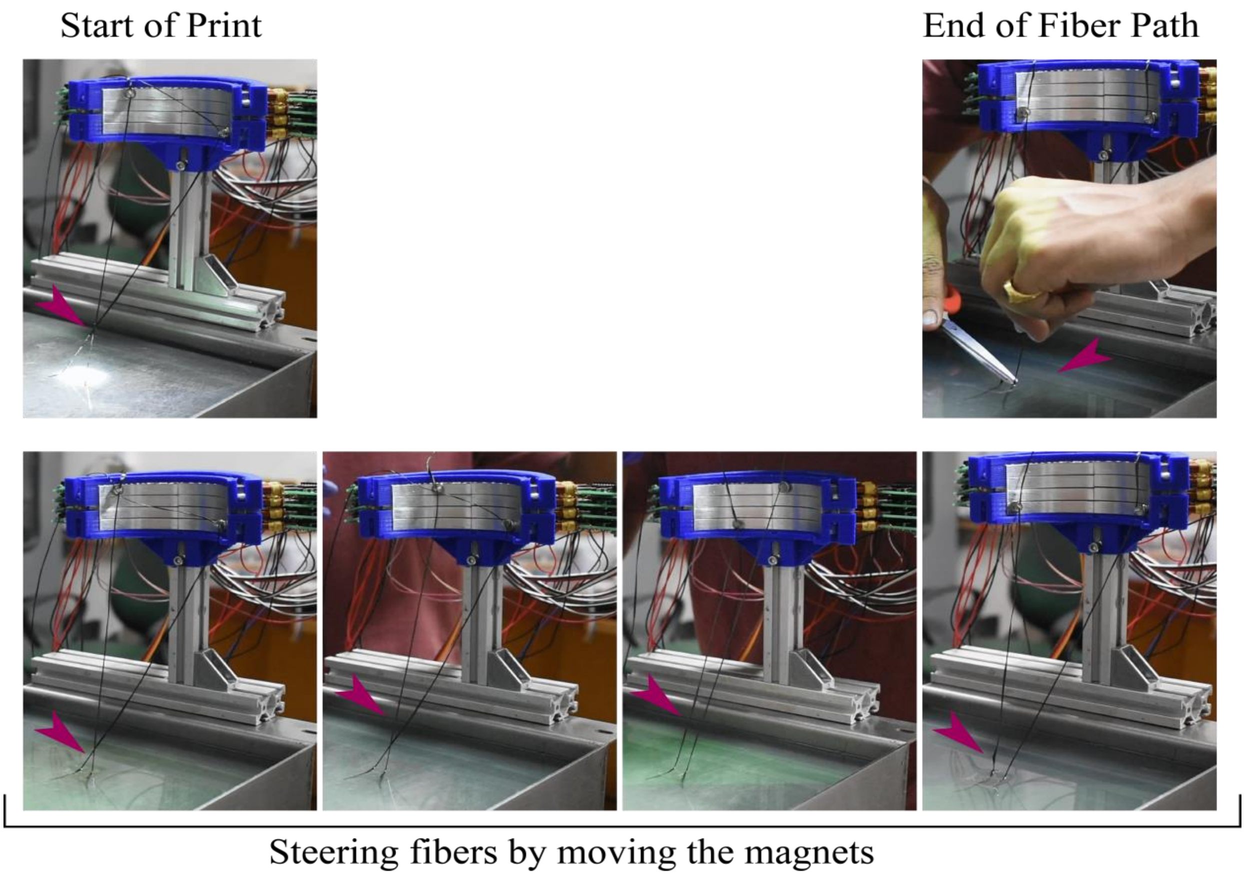

Figure 7: Shows intermediate frames of the process of steering fibers while 3D printing and the annotated arrow (Pink) show the fibers position and orientation due to the movement of the magnets.

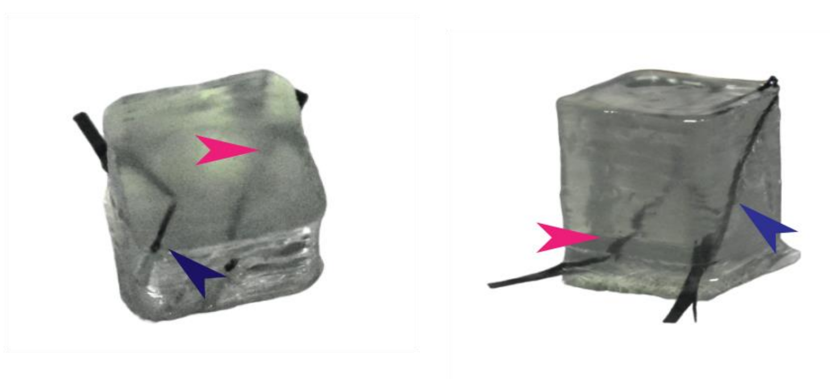

Figure 8: A top and side view of the part printed from the process. The violet and pink point toward respective fiber paths in both the images.

5. Closure

An electromagnet grid of solenoid moved two magnets that steer the fibers in a layer-by-layer vat photopolymerization process. The solenoids were actuated in an intermittent manner to pull the magnets to the adjacent coils. Such robotic platforms can be employed to steer fibers and cure them concurrently with a projector or a light source.

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