MANUFACTURING, PROCESSING AND TESTING OF COMPOSITE CATHETERS FOR NEONATAL PATIENTS

A Thesis Presented

by

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Abstract

The purpose of this thesis is to explore the use of composite fiber reinforcement in neonatal catheters. Current neonatal catheters are extruded from pure polymers such as silicone and polyurethane. While these materials are strong and ductile, improving their mechanical properties with discontinuous fiber composite reinforcement would allow for improved drug flow to patients. With stronger materials, catheter wall thickness could be decreased to increase cross-sectional area for drug flow to patients. Discontinuous Calcium Phosphate fibers are magnetically labeled then aligned with applied magnetic fields during a digital light processing (DLP) printing process. This 3D Magnetic printer is used to produce samples for mechanical testing to evaluate the mechanical properties of varied fiber reinforcement geometries. Several improvements are made to the mechanical components of the printer to improve the resolution, tolerance, quality and yield rate of printed parts. New design concepts are investigated using FEA to improve the magnetic field strength – and therefore printing time – of the 3D magnetic printer.

Further, a UV-curable catheter matrix is developed through experimental testing to achieve comparable material properties to industry standard materials. Bulk material testing of reinforced materials demonstrates significant improvement of mechanical properties when fibers are aligned in the direction of applied stress. As a case study, French 4 catheters were designed and printed to interface with mechanical testing equipment. These geometries will be printed with varied reinforcement architectures in the future to evaluate the strongest types of fiber reinforcement.
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1 Introduction

1.1 Current neonatal catheters

1.1.1 Requirements

Catheters are medical devices used for fluid transfer to or from a patient’s body. These small tubes are most commonly used for drug delivery, but may also be used to remove fluid from the body. Catheters for neonatal patients must have small outer diameters due to the small size of arteries and veins which will be accesses. Catheter size is measured on the French scale, as shown in Table 1. Neonatal catheters range from French 2 to French 4. This geometric requirement adds complexity to achieving the mechanical properties necessary in a catheter.

Table 1: French scale catheter sizes [1]

<table>
<thead>
<tr>
<th>French Size</th>
<th>Inner Diameter (mm)</th>
<th>Outer Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.33</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>0.67</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>1.33</td>
<td>1.67</td>
</tr>
</tbody>
</table>

A catheter must be ductile and flexible enough to be manipulated through pathways in a patient’s body. The catheter must be strong enough to withstand the mechanical stresses of pushing, pulling and bending during its use. The catheter must be able to resist kinking in three-point bending scenarios within the patient’s body.

A neonatal catheter must also have a maximum inner diameter in order to improve fluid flow to the patient. Since the catheter’s outer diameter must be small to fit within the patient’s body, a catheter’s inner diameter can only be increased by reducing its wall thickness. A small increase in inner diameter can significantly improve fluid flow at this scale. As shown by Pouseille’s equation $\Delta P = \frac{128\mu LQ}{\pi d^4}$ (1), the pressure drop along the length of a tube is highly dependent on its inner diameter [2]. A diameter increase of 5% can decrease the pressure drop in a catheter by 17.7%. At the French 2 scale, this means that if the wall thickness is decreased by 0.008mm, fluid flow can be increased by 17.7%.

1.1.2 Materials

Silicone
1.1.3 Manufacturing

Neonatal catheters are manufactured using thermoplastic extrusion processes. The polymer used for the catheters is pre-mixed, cured, and broken into small pieces. These small thermoplastic pieces are loaded into the hopper of an extrusion machine, where they are melted. The liquid thermoplastic is fed through a heated chamber by positive pressure from a screw where its cross section is shaped by an extrusion die, as shown in Figure 1.

![Figure 1: Mechanical components of continuous tube extrusion process. Plastic pieces are fed through the hopper and pushed forwards through a heater, where a highly viscous polymer is forced through an extrusion die. [4]](image)

1.2 Composite materials

Composite materials offer several advantages over standard thermoplastics. Specifically, composites have a high strength-to-weight ratio and high fracture toughness. Composites consist of two material constituents; a polymer matrix and ceramic or metallic reinforcement materials. High-strength materials typically use ceramic reinforcement such as carbon fibers due to their high strength and lightweight. When mixed with a polymer matrix, the strong but brittle fibers reinforce the tough but weak polymer. This combination creates materials with a high strength-to-weight ratio, as shown by the Ashby plot in Figure 2.
Figure 2: Ashby plot of Yield strength vs. Density, demonstrating composites' strength-to-weight ratio. Composites are comparable to the strength of composites at lower density. Composites are much stronger than polymers with a small increase in density. [5]

Although Continuous-Fiber alignment can significantly enhance the mechanical properties of a part if properly constrained, 

\[
\sigma_{cd} = \alpha \tau_c V_f + \sigma'_m (1 - V_f) \quad (2)
\]

Where \( \sigma_{cd} \) is the longitudinal strength, \( \alpha \) is the aspect ratio of the fiber in the direction of loading, and \( \tau_c \) is the bond strength between the fibers and matrix [6]. The elastic modulus of discontinuous fiber composites can be found using equation 2.

\[
E_{cd} = KE_f V_f + E_m V_m \quad (3)
\]

Where \( K \) is the rod efficiency pre-factor, \( V_f \) and \( V_m \) are the volume fractions of the rod and the matrix, respectively, and \( E_f \) and \( E_m \) are the moduli of elasticity for the rod and matrix, respectively. The pre-factor depends on the anisotropy and chemistry of the materials [7].

There are a few key takeaways from these equations to create strong discontinuous-fiber composites. First, the alignment direction is critical to the part’s longitudinal strength. If a fiber is aligned perpendicularly to an applied force it will have a very low \( \alpha \) value, significantly reducing longitudinal strength.

Conversely, aligned fibers will significantly increase the part’s strength. The effect of the fiber alignment angle on a part’s longitudinal strength is visualized in Figure 3, where the tensile
strength clearly decreases as fibers are decreasingly aligned. Additionally, the volume fraction of fibers will significantly increase the part’s strength. Since $E_f > E_m$, if $V_f$ increases then $E_{cd}$ will increase.

![Graph showing tensile strength vs. fiber alignment](image)

**Figure 3**: Tensile strength vs. Fiber alignment for arbitrary material. Composites perform well under loading conditions along their fibers’ long axes, and visa versa. [8]

### 1.3 Current composite 3D printing

Manufacturing processes for continuous fiber composites have been established for years and proven in a wide range of industries. However, new technologies like 3D printing are opening up new doors for composite applications. These new technologies can be broken down into two primary categories – continuous and discontinuous fiber reinforcement.

Markforged has developed the capability to embed continuous fibers within a printed part. Their FEA software is used to determine optimal placement of continuous fiber strands along the direction of an FDM (Fused Deposition Modeling) printed part. This technology enables the manufacturing of high strength-to-weight ratio parts with a high level of geometric complexity. However, the resolution of these printers and fiber reinforcement method is not capable of more complex fiber reinforcement geometries at the micro scale. [9]

At Harvard, Jennifer Lewis’ lab has demonstrated the capability to align discontinuous fibers in FDM printing using the effects of shear flow [10]. Arevo Labs takes advantage of the same phenomena and optimizes fiber placement using FEA software [11]. This alignment technique allows for some degree of tunable fiber alignment, but the alignment direction is restricted to the direction the print head’s motion in the XY plane. Additionally, fibers cannot be aligned in any
out-of-plane direction. These limitations restrict the capability of properly reinforcing complex geometries.

Figure 4: Shear alignment of discontinuous fibers during extrusion-based printing processes. Discontinuous fibers are aligned along the direction of extrusion, limiting reinforcement to planar loading conditions. [10]

1.4 3D Magnetic Printing

1.4.1 Process

Previous work in Northeastern University’s DAPS (Directed Assembly of Particles and Suspensions) laboratory has demonstrated precise control over discontinuous fiber alignment using magnetic fields. The surfaces of fibers are coated with magnetic Iron Oxide nanoparticles which enable magnetic response to an applied magnetic field. This technique has yielded precise control of mechanical properties in aligned materials. [12] [13]

The DLP (Digital Light Processing) magnetic printer was designed and built to implement magnetic fiber alignment into a practical manufacturing process. The DLP printing process is inherently supportive of magnetic field integration. With a stationary printing reservoir, a magnetic field is applied to align all fibers in the same direction. Distinct regions can then be cured with fibers aligned in that direction.

Figure 5 highlights the fundamentals of DLP 3D Magnetic Printing. First, a magnetic field is applied in the desired alignment direction for discrete areas of a layer of a printed part. Once the fibers are aligned, the discrete area is polymerized using a projected image from a UV light source. These steps can be repeated for other areas of a layer to achieve different fiber alignment directions. Once a full layer is polymerized, the Z axis lifts the printed part up one layer, and the next layer is printed.
Figure 5: Alignment and selective UV polymerization of layer-by-layer magnetic DLP printing process. A magnetic field aligns all fibers in the reservoir. Areas of a layer are selectively cured to lock fiber alignment. Adjacent voxels can then be aligned in a different direction and cured. The Z axis then moves upwards for this process to be repeated on the next layer. [12]

This printing process has previously yielded the highest-ordered control of discontinuous fiber alignment to date [12]. As shown by Figure 6, fiber alignment has been demonstrated in distinct regions as small as 90 microns. This 3D magnetic printing process is capable of orienting fibers in any direction throughout complex parts.

Figure 6: Programmable control of fiber-reinforced microstructures. Previous work in the DAPS lab has demonstrated control of distinct fiber alignment directions in regions as small as 90 microns. [12]

1.4.2 Catheter applications

Aligned discontinuous fiber composites have many potential biomedical applications. Biocompatible polymers can be reinforced to finely tune a part’s strength properties for specific applications. One potential application is to reinforce the materials used in neonatal catheters to improve drug delivery.

Catheters reinforced with discontinuous Calcium Phosphate fibers will improve strength while maintaining flexibility and biocompatibility. With stronger materials, wall thickness may be
reduced in order to increase the inner diameter. These materials may enable the manufacturing of catheters which meet the size and mechanical requirements for catheters while improving drug delivery capabilities.

In order to validate this hypothesis, catheters will be manufactured using the 3D Magnetic Printer developed in the DAPS lab. Samples will be manufactured in the DAPS lab and tested in conjunction with N2Biomedical, according to the SBIR grant funding this research.

A polymer material will be developed for use as the catheter’s composite matrix. This material will be developed to match the properties of polyurethane used in catheters as closely as possible. Once this material is selected, the primary study of this project will focus on the relationship between fiber alignment direction and material strength. The directional orientation of a fiber within the composite will significantly affect the catheter’s mechanical properties. In order to determine the optimal fiber alignment geometry, several types of alignment will be mechanically tested and compared with each other.

2 DLP printer design and procedural improvements

2.1 Introduction to design

As a part of this project, several significant design modifications were implemented to improve the quality and yield rate of the DLP printer. Significant portions of this project have been geared around product design and processing improvements to improve the end result of printed catheters. These improvements range from the design of mechanical components to the improvement of magnetic field strength in the device. Additional work has included the design, prototyping and testing of a direct-write printer that was previously designed to broaden the manufacturing capabilities of 3D magnetic printing.

The system layout can be seen in the cross section shown in Figure 7. The figure includes labels of several major system components which will be referenced throughout this paper. The DLP printer is mounted on a frame made using 80/20 Aluminum extrusions. The reservoir contains the UV-curable composite matrix on top of a thin, transparent film to allow for UV-polymerization from the projector below. The reservoir base sets the location of the printing plane, since the thin film is tensioned on a flange in its center. Therefore, it is important that the reservoir base is properly leveled in order to achieve prints with uniform layer thickness.

The only moving parts on the printer operate in the Z direction. Two stepper motors are fixed to the Z axis mounting plate and control the rotation of lead screws, which control the height of the gantry. Tightly-constrained linear rods are also fixed to the gantry and Z axis mounting plate to constrain motion error in the XY plane. These linear rods guide the horizontal position of the gantry, while the lead screws control its height.
The gantry serves as an interface between Z axis motion and the build plate. The aluminum build plate is the surface that a printed part adheres to. The build plate will lift the part out of the reservoir as it is printed, layer-by-layer.

Four solenoids with soft magnetic core materials are oriented orthogonally about around the printer to create magnetic field components in the X and Y directions. A fifth solenoid without a core material is oriented under the printing reservoir without a core material. This solenoid creates a magnetic field component in the Z direction while allowing light to pass through for UV polymerization.

![DLP system CAD cross-section and labeling of major mechanical components. Orthogonal solenoids control magnetic field in reservoir, where UV light from the projector selectively cures a part layer-by-layer.](image)

### 2.2 Magnetic control

#### 2.2.1 Current magnetics design

To control fiber alignment throughout a print, the magnetic field must be well characterized throughout the printing material reservoir – specifically at the building surface. The electromagnetic control system for the DLP printer relies on the concept of magnetic field vector superposition. The flux density magnitude and direction of intersecting magnetic fields follow
basic properties of vector addition, as shown by the addition of vectors A and B in equation $\vec{A} + \vec{B} = A_x \hat{i} + A_y \hat{j} + A_x \hat{k} + B_x \hat{i} + B_y \hat{j} + B_z \hat{k} = (A_x + B_x) \hat{i} + (A_y + B_y) \hat{j} + (A_z + B_z) \hat{k}$ (4).

$$\vec{A} + \vec{B} = A_x \hat{i} + A_y \hat{j} + A_z \hat{k} + B_x \hat{i} + B_y \hat{j} + B_z \hat{k} = (A_x + B_x) \hat{i} + (A_y + B_y) \hat{j} + (A_z + B_z) \hat{k}$$ (4)

Four electromagnets with Low Carbon Steel soft magnetic cores are positioned orthogonally on all sides of the build plate – two controlling the magnetic field’s Y component and two controlling the X component. The soft magnetic cores have a high magnetic permeability, which amplifies an externally applied magnetic field [14]. The low carbon steel cores amplify the flux density by a constant factor of about 1.5 times in this system. Additionally, an electromagnet is positioned below the build plate without any core material to create the magnetic field’s Z component while allowing the projector’s light through. The manufactured setup is shown in Figure 8.

By controlling the polarity and magnitude of current through each solenoid, any resultant magnetic field direction may be achieved. In order achieve optimal control of a printed part’s mechanical properties, the magnetic field direction should be controlled within a tolerance of $\pm 15^\circ$ to achieve a reasonable, but challenging magnetic field resolution.

This system has demonstrated field accuracy within tight tolerances throughout the build plate that are within the goal of $\pm 15^\circ$ field direction resolution. However, both FEA and experimental results show that the XY field direction resolution outside the system’s build plate is quickly
skewed. Planar field direction error is caused by two factors: field curvature and magnitude variation of each field component throughout the XY plane.

Cylindrical solenoids have inherent elliptical curvature of flux density lines outside their center. The curvature of the magnetic field is shown by the direction of flux density vectors mapped in Figure 9. The direction of this Y-direction field has increasing error compared to the radially away from the center of the solenoid. The field magnitude error is also shown in Figure 9 by the magnitude of flux density vectors and by the color of each element. The field gets significantly weaker at points farther away from the front face of the solenoid.

Figure 9: 2D Axisymmetric FEA solenoid representation. The model on the left shows the node placement and material properties of sections of the FEA model. The blue lines outline the material boundaries of different areas of the part. The line at the left of the model represents the central axis of the cylindrical solenoid. The results on the right demonstrate the flux density magnitude and direction. The vectors represent the direction and magnitude of the magnetic field, while the colors represent the magnitude of flux density throughout the model.

Both of these types of error compound to create a maximum XY planar field direction resolution error when trying to achieve a 45° angle with respect to the printer’s X axis. Any resultant field direction that requires equal field strength from each axis will create a maximum field direction error in the printing plane, including 45°, 135°, 225° and 315° alignment directions. This observation comes from FEA modeling of different resultant field directions. Conversely, the best-case alignment tolerance scenario is an alignment direction that is along the X or Y axes at 0°, 90°, 180° or 270°, because the additional error caused by superposition of orthogonal solenoids is eliminated.
Using FEMM (Finite Element Method Magnetics) software, the XY plane of the printer can be represented in 2-dimensional form. A cross section of the mid-plane of each X and Y solenoid is represented in Figure 10.

![Diagram of a 2D representation of a magnetic system showing fields in a plane with material properties and current distribution.](image)

**Figure 10: Planar FEA representation of current magnetic system.** Blue lines separate discrete regions of the cross section, with material properties applied to each section. The current active printing area is pictured in the center of the model as a reference. Based off the size of 18AWG wire used and the area of the wire’s rectangular cross-section, the total current passing through each rectangular cross-section at any applied current can be calculated and input into the model. Positive current on one side of the solenoid and negative current on the other side are used as a planar representation of field conditions in cylindrical solenoids.

In order to study field resolution issues, the worst-case scenario of a 225° angle is modeled in Figure 11. Upon visual inspection, the field direction and magnitude varies significantly throughout the XY plane. The worst cases are along the X and Y axes, where each axis’s field directionality is exactly where it should be, but the magnitude of one axis dominates at points farther from the axis of another. For example, at a point halfway between the center of the build plate and the inner face of a Y solenoid (0, 1.75), the angle is 239°. This means that in order to achieve acceptable field direction, the build plate can only occupy the central 25% of the area between the solenoids.

Additionally, at the upper right corner of a build plate limited by the axial angular tolerance described above (1.75, 1.75), the magnitude of the field is 102.3 Gauss, just 53% of the field strength in the middle (193.1 Gauss) of the build plate. Conversely, at the upper left corner of the build plate (-1.75, 1.75), the field strength is 156% (302.1 Gauss) that of the build plate center.
The differences between acceptable field angle ranges will be further discussed in section 2.2.4. Despite some of the weaknesses in current solenoid design outlined, the build plate is well within the acceptable field tolerance range at ±7°.

![Figure 11: 45° XY plane field resolution of current DLP system. Flux density direction and magnitude is represented with vectors throughout the model. Flux density magnitude is also represented with a color gradient corresponding to the vectors’ magnitude.](image)

### 2.2.2 Iterations on current magnetics design

The most straightforward way to improve field strength is to apply higher currents to the solenoids. However, as more current is applied to the solenoid more heat is generated. Currently, the solenoids are operated at 3A to maintain a steady state solenoid surface temperature around 50°C. As higher currents are passed through the solenoids the added heat risks damaging the electrically isolating enamel coating on the solenoid surfaces.

The possibility of using thicker-gauge wires was explored. However, the fundamental relationship between heat generation quickly highlighted that the heating problem could not be avoided with thicker wiring.

Increasing a wire’s cross-sectional area reduces its resistance significantly. However, in order to maintain the same magnetic field as a smaller wire, the applied current must be increased to
maintain a constant current flux through the wire. Equations \( R = \frac{4\rho L}{\pi d^2} \) (5) through 

\[ Q \left( \frac{W}{m^2} \right) = \frac{P[W]}{A[m^2]} = \frac{i^2R}{A} = C\rho L \] (7) demonstrate that heating is constant regardless of a solenoid’s wire gauge. Heating is created by a wire’s resistance, which is dependent on a wire’s resistivity \( \rho \), length \( L \) and diameter \( d \). As a wire’s diameter increases, the current flux will have to remain constant in order to maintain the same magnetic field strength. Therefore, the current, \( I \), is dependent on the wire diameter and a constant current flux factor, \( C \), with units of A/m². The heat flux in the wire’s cross section, \( Q \), is calculated based on the power going through the wire, \( P \), divided by the wire’s cross-sectional area. From this equation it is clear that heat generation in a solenoid is not dependent on the wire diameter used. Therefore, the field strength cannot be increased in the current solenoid design without implementing a cooling system.

\[ R = \frac{4\rho L}{\pi d^2} \] (5)

\[ I = \frac{c\pi d^2}{4} \] (6)

\[ Q \left( \frac{W}{m^2} \right) = \frac{P[W]}{A[m^2]} = \frac{i^2R}{A} = C\rho L \] (7)

The solenoids’ core geometry may be modified in order to improve magnetic field strength while maintaining field directionality resolution in the build area. Field strength has a crucial effect on printing speed, since the magnetic torque that causes fiber alignment is proportional to the flux density squared [13]. Therefore, small increases in flux density result in significantly faster fiber alignment times.

Two fundamental geometry changes can be considered to revise the current solenoid design. The soft magnetic Low Carbon Steel core material may be extended on the front face of each solenoid towards the build plate, or off the back of the solenoid away from the build plate. Both options may increase flux density in the build plate.

FEA was used to evaluate various core geometry concepts using a 2-dimensional planar FEA model as described in 2.2.2. The flux density at the center of the build plate is recorded for each model and compared to FEA results for the current DLP solenoid design.

Intuitively, extending the core material towards the build plate would likely increase field strength. However, the 1-inch core extension in the model shown in Figure 12: Maximum inner core extension FEA model resulted in a significantly weaker field than the current design. As shown in Figure 13, the magnetic field of one axis is more easily drawn into the soft magnetic core of the other axis, resulting in a 17% lower flux density in the build plate.
Figure 12: Maximum inner core extension FEA model. The cores are extended towards the printing plane with the intent of increasing the magnetic field in the build area.

Figure 13: Extended cores, X direction field warping. Despite increasing the amount of core material, the field is weakened as a result of field warping from the cores of the orthogonal axis.

This observation is further supported by a FEA model with cores extended only on the X axis as shown in Figure 14: Extended X cores. Without the Y axis cores extended, the field lines are not as warped and the field is amplified by 19% in the center of the build plate. These models demonstrate that core extension on the inner faces of the solenoid does not trivially increase flux
density. However, fields may be increased in extended core designs by reducing field warping effects of perpendicular extended cores.

![Image of Extended X cores](image)

**Figure 14:** Extended X cores. By not extending the cores of the perpendicular axis, the field warping does not decrease the magnitude of the field compared to the current design. This model serves as an investigative design, not a feasible system design.

If the core material is extended towards the build plate but only as wide as the build plate, flux density reduction caused by field direction warping is reduced and the field becomes stronger. The model shown in Figure 15 results in a 26.5% increase in field strength.
Figure 15: Modified front core. The cores are only extended to be slightly wider than the build plate. This increases the field strength without warping the field as much from the orthogonal solenoid axes.

Extending the core off the back of the solenoid may also increase field strength. The model in Figure 16 depicts a core extension of 2 inches off the outer face of each solenoid. This extension resulted in a field strength increase of 20.7% compared to the current design. Similar extensions with different lengths suggested that outer face core extension continues to increase flux density as length is added. Therefore, cores may be extended as far as physically allowed by the system’s design.
Figure 16: Outer core extension. Extending the solenoid core material off the outside of each solenoid significantly increases the field strength without warping orthogonal field lines.

Based off these results, it may be advantageous to extend the core off the back and front faces of the solenoid. This hybrid design is modeled in Figure 17. The core material is extended to the maximum lengths of the front and back of the printer that are allowed by the printer’s geometric constraints. This design results in a flux density that is 55% stronger than the current DLP printer’s magnetic design. This will increase magnetic torque by 125%, which will reduce fiber alignment times by more than 50% based on equation $T_{mag} = \frac{4\pi\mu_0 X_p s^2}{3(X_p s + 2)} [(A + d)(B + d)^2 - AB^2] H_0^2 \sin\phi \cos\phi$ (17. Field strength comparisons for all FEA designs presented are shown in Table 2.)
Figure 17: Hybrid core extension design for new DLP printer. A combination of core extensions off the inner and outer face of each solenoid significantly increases flux density in the printing area.

Table 2: Flux density comparisons of revised DLP magnetic core designs

<table>
<thead>
<tr>
<th></th>
<th>3A Flux Density (G)</th>
<th>Current SLA</th>
<th>Front 1-inch Extension</th>
<th>Single front 1-inch extension</th>
<th>2 Inch Back Extension</th>
<th>Narrower front extension</th>
<th>New SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>45deg Field</td>
<td>193.0</td>
<td>160.0</td>
<td>N/A</td>
<td>233.0</td>
<td>244.2</td>
<td>300.0</td>
<td></td>
</tr>
<tr>
<td>X field</td>
<td>136.7</td>
<td>113.6</td>
<td>163.0</td>
<td>165.0</td>
<td>176.6</td>
<td>216.9</td>
<td></td>
</tr>
<tr>
<td>Y field</td>
<td>136.7</td>
<td>113.6</td>
<td>N/A</td>
<td>165.0</td>
<td>168.7</td>
<td>206.6</td>
<td></td>
</tr>
</tbody>
</table>

It is important to note that due to the narrower inner core extension on the Y axis, the Y axis flux density is 5% weaker than the X axis. As a result, the field strength of one axis will have to be offset by a constant factor in order to achieve accurate angular resolution of combined resultant fields. This offset factor was applied to the FEA model in order to achieve a 45° angle. The model was then analyzed for angular tolerance at critical points of the build plate.

The modified magnetic design has a maximum field direction error of ±15°. While this is an acceptable number for all directions to be within, some higher-resolution prints may require less inner core extension in order to improve field direction resolution.

2.2.3 Automated magnetic field direction integration

In order to streamline the 3D magnetic printing process, the direction of the applied magnetic field was integrated into the printer’s G code communication. G-code magnetics integration was previously demonstrated as a part of a capstone project on a direct-write magnetic printer. That
printer relied on H-bridge circuits with PWM (Pulse Width Modulation) capabilities to control the magnitude of current applied to three orthogonal solenoids. [5]

This magnetic control system was modified to satisfy the design constraints of powering five much larger solenoids operating at higher currents and voltages than those in the direct-write printer. The original electronic circuits were modified to accommodate these electrical differences. Additionally, high-voltage power supplies were selected using Ohm’s Law (equation $V = IR$ (8)).

$$V = IR \quad (8)$$

The solenoids have a resistance of 7.9 $\Omega$. Therefore, to achieve a target maximum current of 6A, the DC power supplies will have to be 48V. One 48V 7.3A power supply is used to power each solenoid through the electronic control board. These power supplies and electronic control system are shown installed in

![Figure 18: Power supplies and electronics for magnetic control system. Each of the five solenoids is run of its own 48V power supply and electronic control board. An Arduino board controls the magnitude and direction of current to each solenoid.](image)

The Arduino code powering the PWM and H-bridge of each circuit was modified to calculate the magnitude and direction of power required for each of the five solenoids in the DLP printer in order to achieve any input alignment direction.

The matrix multiplication algorithm previously developed was modified to adjust for the different axis directions of the DLP printer. With that simple modification, the percentage of field strength required in each axis of the magnetic control system was calculated. In order to
create complementary fields with the two magnets in both the X and Y axes, both magnets on the same axis are powered with the same magnitude of current but inverse polarities.

The following matrix multiplication was previously developed for the direct-write system and modified slightly for the DLP printer [5]. The \([S]\) matrix represents the axis direction of each solenoid in the printer’s coordinate system as a unit vector. The \([D]\) matrix represents the desired resultant magnetic field direction as a vector. This direction matrix is normalized to \([D_N]\). \([p]\) represents the percentage of each solenoid’s full scale current to achieve the desired resultant field direction. \([P]\) represents the analog PWM value that will control the current to each solenoid. The maximum PWM value is set to limit the current of the solenoid to a maximum value.

\[
[S] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\] (9)

\[
[D] = \begin{bmatrix} x_D \\ y_D \\ z_D \end{bmatrix}
\] (10)

\[
[D_N] = \begin{bmatrix} \frac{x_D}{\sqrt{x_D^2 + y_D^2 + z_D^2}} \\ \frac{y_D}{\sqrt{x_D^2 + y_D^2 + z_D^2}} \\ \frac{z_D}{\sqrt{x_D^2 + y_D^2 + z_D^2}} \end{bmatrix}
\] (11)

\[
[p] = \begin{bmatrix} p_{x_1} \\ p_{y_1} \\ p_z \end{bmatrix}
\] (12)

\[
[S][p] = [D]
\] (13)

Therefore,

\[
[S]^{-1}[D] = [p]
\] (14)

\[
p_{x_2} = -p_{x_1}, \quad p_{y_2} = -p_{y_1}
\] (15)

\[
[P] = (\text{maximum PWM value}) \times [p]
\] (16)

Since the X and Y field magnitudes are equal at the same applied current, the Z solenoid’s applied current was calibrated based on the relative flux densities of the Z axis field and the X
and Y fields at different applied current levels. These calibration results are shown in Table 3, where the flux density of each axis was measured using a Gaussmeter probe.

The proportion of the Z axis flux density to the X and Y axis flux density was calculated at each measurement point. The Z axis consistently measured an average of 70.97% of the field strength of the X and Y axes with a standard deviation of 1.66%. As a result, the magnitude of power calculated through the field direction algorithm will be multiplied by a constant factor of 0.7097 in the magnetics control code. The magnetic control code for the DLP printer is included in section 6.1.

The data also indicate that the Y field is slightly stronger than the X field. However, due to the potential human factors of error with the placing of the Gaussmeter probe, they are assumed to have equal field strengths at the same current.

Table 3: Calibration of DLP magnetic field strengths

<table>
<thead>
<tr>
<th>PWM Value</th>
<th>Current (A)</th>
<th>Flux Density (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>50</td>
<td>1.18</td>
<td>80.2</td>
</tr>
<tr>
<td>100</td>
<td>2.35</td>
<td>154.5</td>
</tr>
<tr>
<td>150</td>
<td>3.53</td>
<td>229.25</td>
</tr>
<tr>
<td>200</td>
<td>4.71</td>
<td>297.6</td>
</tr>
<tr>
<td>255</td>
<td>6.00</td>
<td>368</td>
</tr>
</tbody>
</table>

2.2.4 Finite element analysis of U-magnet control systems

In order to address the problem of magnetic field direction and magnitude uniformity between the inner faces of magnets, fundamentally different magnetic control system concepts may be considered. Specifically, U magnets are a potentially ideal solution to this issue.

U-shaped electromagnets create a field with uniform direction and nearly uniform flux density distribution between the tips of the ‘U’. Additionally, where the strongest field lines in a cylindrical solenoid wrap closely around its edges, the strongest field lines of a U-shaped magnet pass through the core material and through the space between the ‘U’ tips [15]. A well-designed U-shaped electromagnetic control system may increase the usable build area and increase electrical efficiency.

FEMM software is used to investigate the effectiveness of U-magnet concepts. A U-magnet can be modeled using a soft core material in a U shape with positive current running through wire on one side and negative current on the other side, as shown in Figure 19. For each model, the current passing through 12AWG wire was normalized based off the cross-sectional area of the inner wire section in the FEA model. Based off that area, the total current passing through the cross section was calculated for 1, 3 and 5A applied currents to 12AWG wire.
Figure 19: U-shaped electromagnetic FEA model. The central core material is bordered by positive and negative currents in a 2D planar model.

For each model, the flux density was measured at 100 incremental points between the tips of the solenoid on the mid-plane of the core material. The tangential and normal flux density to the red line shown in fig were recorded at applied currents of 1, 3 and 5A. From these measurements, the total flux density and angular flux density error in the Z direction could be calculated.

Figure 20: U-shaped electromagnetic FEA results and measurement. The highest flux density in free space is between the tips of the solenoid where the field direction is highly controlled. The field magnitude has only small variations between the tips of the solenoid.

Additionally, the total wire length required to wrap the solenoid could be calculated based off the depth of the U magnet, which was not modeled but was based off the distance between tips of the U magnet. Based off wire diameter and length, the solenoid’s resistance could be calculated, which enables the calculation of the total power (in Watts) running through the solenoid.
For each FEA design, a data file describing its properties was produced. Each FEA model output a 1-dimensional array of flux densities between tips of the U-magnet. It is possible to make the assumption that if two of these U-magnets were oriented orthogonally, their fields would superimpose following standard principles of intersecting magnetic fields. Under that assumption, the flux density direction and magnitude can be plotted throughout the 2-dimensional printing plane for different resultant field directions.

If the elements of the magnet are represented by a 1x100 matrix \([A]\), then the 100x100 element printing plane can be calculated by \([A][A]^{-1}\). This method can be used to calculate both angle and magnitude of the field at any of the elements. Using conditional formatting in Excel, a visual representation of different field tolerance regions can be generated as shown in Figure 21, where the green region represents ±5° tolerance, light green represents ±10°, yellow represents ±15° and orange represents worse than ±15°. For each of these models, the ±10° tolerance zone was numerically calculated as a percentage of the distance between the tips of the U solenoid. This standardized measurement gives a good representation of each design’s usable printing area.

![Figure 21: FEA 2D printing plane directional tolerance for 45° angle. ±5° tolerance zone is represented by dark green, ±10° by light green, ±15° by yellow, and >±15° by orange.](image)

The magnitude of the field strength in these models is also visually represented with conditional formatting in excel as shown in Figure 22. The red regions represent strong fields and green regions represent weaker fields. As expected, the field is strongest near the tips of the solenoid, but quickly evens out into a field with nearly uniform flux density.
The data in Table 4 highlights the comparative differences between FEA models. For each model, the solenoid’s alignment efficiency and usable area with a ±10° alignment tolerance were calculated. From the data it is clear that a thicker core material increases field strength in U magnets. The most important distinction to make is between the U magnet concepts and the current magnetic control system. The best performing U magnet has an alignment efficiency nearly 150% greater than the current design with a nearly 150% larger usable area. The alignment efficiency is only 28% greater than the extended core magnetics design, but has 420% more usable area.

The most telling metric for design comparison is the area weighted efficiency, which is the product of alignment efficiency and the ±10° % of usable area. The area-weighted efficiency provides a metric of both field strength and usable print area, which corrects for outliers like the extended core design which has a high alignment efficiency but low usable area. By this metric, the best performing U magnet performs over 500% better than the current design, and the extended core design does not result in an area-weighted alignment efficiency improvement over the current design.
Table 4: Comparison of FEA models of magnetic control system concepts

<table>
<thead>
<tr>
<th></th>
<th>U magnets</th>
<th>Current Design</th>
<th>Extended Core Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alignment efficiency (G^2/W)</td>
<td>Avg</td>
<td>138</td>
<td>262</td>
</tr>
<tr>
<td>±10° %Usable Area</td>
<td></td>
<td>44%</td>
<td>44%</td>
</tr>
<tr>
<td>Area-weighted efficiency</td>
<td></td>
<td>60.0</td>
<td>114.3</td>
</tr>
</tbody>
</table>

Based off these results, U magnets appear to greatly improve the field strength properties in the XY plane for a DLP printer’s magnetic control system.

It is important to note that these models will not perfectly represent the actual FEA of orthogonal U-shaped electromagnets. The assumption that one magnet will not affect the direction of magnitude of the other’s magnetic field is not accurate. The soft magnetic core material at the tips of one magnet will affect the directionality of field lines from the other, much like the behavior of the magnetic field in Figure 13. For this reason, the assumption made for these models is inaccurate and the actual result will likely deviate from these models, especially near the edges of the printing plane where the orthogonal core material will have the greatest affect.

2.2.5 Experimental results of U-magnet prototype system

A scaled-down U-magnet prototype was designed and fabricated in order to validate the legitimacy of the assumptions about converting 2D FEA models to 3D in section 2.2.4. Low-carbon steel sheet metal was bent into the U-shape using manual bending methods. Enamed copper wire was then wrapped around the solenoid two times from end to end. These solenoids were positioned orthogonally in a 3D-printed fixture. Iron filings were placed between two acrylic sheets in the center of the fixture in order to view the magnetic field’s directionality. This fixture is shown in Figure 23.
Figure 23: Scaled U-magnet prototype. Low-carbon steel cores were bent into U-shapes. Enamel copper wire was wound around each core. Iron filings in the center of the model show field directionality.

Figure 24 shows iron filings aligning along the field direction throughout the printing plane. There is some field direction variability apparent especially near the right edge of the printing plane. However, the vast majority of the printing plane appears to have uniform directionality.

Figure 24: Field direction uniformity of U-magnet prototype. Iron filings demonstrate high field uniformity throughout scaled printing plane.

There were several sources of error in this prototype system. Since the cores were bent using manual methods like a vise, the cores were manufactured with an asymmetrical shape. Additionally, the ends of the cores were not cut perfectly. Instead, the core tips are angled, which adds to core error. The solenoid wires were wrapped manually around the length of the solenoid, which almost certainly introduced a non-uniform distribution of current around the solenoid.
These factors are likely to have created field gradients that were not consistent with FEA modeling.

However, the primary result from this prototype is that 3D U-magnets do seem to demonstrate a comparable level of angular tolerance to the FEA models in section 2.2.4. While some further level of testing may be required to validate this system before scaling the control system to the printer’s size, the prototype seems to indicate a comparable or improved field directionality. In conjunction with improved solenoid efficiency, the U-magnet design may be a significant improvement over the current DLP printer’s magnetic design.

### 2.3 Print reservoir modifications

The mechanics of the printer’s peel function are essential to DLP printing. After each layer is cured, it is adhered to both the aluminum build plate and the transparent reservoir base. The build plate lifts up from the reservoir and the printed part must separate from the reservoir base and stay adhered to the build plate. It is critical that the reservoir base material allows UV light to pass through and cure the part, and that the bond between the base material and the part is weaker than the bond between the part and the aluminum build plate.

Previous printer designs have relied on glass plates with silicone surface treatment to enable these two properties. However, the peel function was often unsuccessful due to variability in the silicone layer and the mechanics of peeling away from a rigid surface.

In order to improve peel mechanics, a commercially-available flexible Teflon build reservoir system was purchased [16]. The thin, transparent film is tensioned like a drum under the build plate. The film allows light through and is rigid enough to allow for accurate Z resolution, but flexible enough to allow the part to peel away from the reservoir base less violently than a rigid surface.

The purchased film was originally tensioned with a 3D printed fixture. While these parts lasted for a few prints, they would quickly breakdown due to solvents in the printer material. They also could not create enough tension in the Teflon film to accurately print parts without inducing catastrophic mechanical stress.

An aluminum base, reservoir and tensioning system was designed to implement this build plate as a long term solution in the printer. The design shown in Figure 25 allows for low-cost replacement of the build plate Teflon film when necessary without ever needing to replace the other build plate components.
Additionally, the reservoir design enables the implementation of heaters to control the temperature, and therefore viscosity, of the material in the printing reservoir. The material viscosity directly affects the alignment time of fibers suspended in the material. If the material is heated, fiber alignment times and therefore print times can decrease. The two cartridge heaters are controlled in G-code using the commands M104 SXX; and M140 SXX; - where XX represents the set point temperature in degrees Celsius.

While a flexible reservoir enables a less violent peeling motion, it also introduces another variable to the homing location of the Z axis. Instead of homing against a hard surface like the glass plate, the build plate is now homing against a flexible surface. The previous displacement-based design would home at the same location each time if the Z stop was in the same location. In the new design, the Teflon film’s tension becomes a variable that may affect the thickness of the part’s first layers. This is largely caused by the viscosity of the fluid being printed.

If the fluid has a high viscosity and the build plate’s zero location is exactly on the plane of the Teflon film, the fluid trapped between the build plate and the Teflon film will not escape. This causes the Teflon film to be pushed down in a parabolic shape. This effect is noticeable especially with more viscous fluids or if the build plate has been zeroed too low.

Figure 26 shows a part that was cured with a parabolic first layer. The Teflon film tension, Z zeroing height and fluid viscosity all play a critical role in the success of a print.
2.4 Peel function

Since implementing the flexible print reservoir base, the peel function has had a much higher success rate and prints are produced more consistently. However, additional hardware updates were also required to reduce mechanical stress on the Z axis components. The printer’s peel function separates the cured part from the Teflon film by raising one side of the build plate, then the other. The angled bias of this displacement motion makes the part peel from one corner to the other.

While this motion creates a less turbulent separation of the part, it also requires more force on the first stepper motor to raise than the other. Since the vertical motion of the z axis is tightly constrained by the linear rods, the gantry is not free to move vertically at large angles. This results in a skipping motion as the gantry is raised, and causes the first flexible lead screw coupler to extend more than it is designed to because it cannot withstand the amount of force introduced in large angle peel motion. In one case this resulted in fatigue failure of the lead screw coupler.

It was also noticed that the stepper motor would often reach its torque limit and skip during the first part of the peel motion. This caused the first motor’s Z location to be offset from the other’s, resulting in an angled build plate that did not print properly and causing further system vibration and skipping during z motion.

The peel function’s mechanics were modified in order to reduce fatigue and error on the first Z axis lead screw. Instead of moving one screw the full distance of the peel followed by the other, an “inchworm” style peel was developed in the printer’s firmware. The first motor first lifts a set incremental distance between 1-1.5mm. The second motor follows, lifting to a point that is slightly below the first motor. This motion repeats until the desired peel height is reached and the second Z lead screw matches the other’s height. This code is included in section 6.3.

This motion still achieves vertical displacement with an angled bias while significantly reducing the stress on the first lead screw’s coupler. Since introducing this peel function to the firmware, the Z axis does not need to be recalibrated nearly as much as before since the first motor does not skip during the peel.

2.5 Z axis motion

The motion of a DLP printer’s Z axis must be highly constrained in order to achieve high resolution in the XY plane. If the Z axis is not tightly constrained, the printer may return to a different location after the peel function if mechanical causes some type of misalignment of the
printer’s lead screws. In order to constrain lateral motion of the build tray, the printer’s linear rods must be constrained both above and below the build plate.

Previously, the linear rods were only constrained at the top of the printer. This resulted in Z axis play that occasionally was noticed in non-uniform cross sections, and could be observed during the peel function. Close fit holes were incorporated into the reservoir base in order to constrain the linear rods. These constraints prevent any further error in the positioning of the build plate in the XY plane.

The constraining of the lead screws and linear rods at the top of the Z axis is essential to achieving smooth linear motion. Any error in the positioning may result in gantry vibration which decreases printer resolution and component longevity. The stepper motors and linear rods were previously constrained with two separate machined aluminum plates.

This design resulted in a difficult calibration process and calibration error. Since the distance between the two plates could vary and the stepper motors were constrained in slots, the relative position of the lead screws and linear rods was not tightly constrained. If the linear rods were then constrained at the bottom of the Z axis as they should be, the error would be immediately noticeable due to gantry vibration.

In order to eliminate this error, the two plates were replaced with a single Z axis plate. The plate has tightly-constrained close fit through holes for mounting the stepper motors and linear rods. Additionally, the plate was machined so that the top and bottom surfaces are parallel within a tight tolerance. As a result, the printer’s motion in the Z direction was improved significantly.

The position of the lead screws and linear rods no longer needs to be calibrated regularly, and the XY plane tolerance of the printer should be intuitively increased.

2.6 **Build plate calibration**

In order to calibrate the printer, leveling with respect to gravity is used as a baseline for different components. First, the printer itself must be placed on a level surface or leveled with its leveling feet. Second, the motion stage mounting plate must be with respect to gravity. The gantry must then be leveled by manually turning the lead screws of the printer. Third, the build plate itself must be leveled using the 3 leveling screws attached to the gantry. The build plate will be further calibrated off the printing plane when zeroing the Z axis.

The reservoir base must also be leveled with respect to gravity. There are high tolerance stackups in the print reservoir, from the positioning of the 80/20 Aluminum on the printing stage base to the flexible polycarbonate mounting plates for the Z solenoid. As a result, shim material often has to be used to achieve a level build reservoir.
2.7 **Build plate zeroing**

The printer’s zeroing location is critical to the print success rate. Previously, the printer’s end stop was fixed on the printer’s linear rod and would be triggered when the gantry came in contact with it. This method often resulted in a long calibration process that would have to be frequently redone. If the linear rod was ever moved up or down or rotated, the Z stop would change position.

To alleviate this issue, a traditional set screw Z stop system was designed. The Z stop itself is positioned in a fixed location on the build reservoir, and therefore is always in the same relative position to the build reservoir surface. A fixture was 3D printed to constrain the set screw. This system allows for fine tuning of the Z axis zero location that is repeatable from print to print.

![Image](image.png)

Figure 27: Z stop positioning on reservoir base plate enables highly-accurate and repeatable Z axis positioning.

The flexibility of the Teflon build reservoir surface allows for the Z zeroing process to be based off of manual feeling of the distance between the build Teflon film and the build plate. In order to find the proper zero location, the printer’s operator can push up on the Teflon film and feel the distance between the film and build plate.

Throughout this iterative zeroing procedure, the printer’s operator must take note of a few variables. First, the operator must be cautious of zeroing too low. This is usually indicated by a parabolic film shape where the separation between surfaces is greater in the middle than the sides of the build plate. Second, the relative leveling of the build plate and the film must be checked by feeling for discrepancies in the separation distance from side to side and front to back of the build plate. If one section is closer to the build plate than another, the build surface leveling screws must be adjusted appropriately.

During this process, it is crucial to take note of the properties of the Teflon film’s curvature. Especially with new materials, the build plate tension and Z zeroing location can be critical to achieving successful prints. This procedure is increasingly important with high fiber volume fraction materials. First layer adhesion can be a big challenge for these materials due to the UV light penetration depth reduction from light interference caused by fibers. The printer operator
must minimize the distance between the build plate and film in order to increase the success rate of first layer print adhesion.

2.8 Software printing control

2.8.1 First layer height

After a part is sliced, a few manual g-code edits are used to improve the print quality. Since the first layer print adhesion is a major variable and the zeroing location is determined manually, it is helpful to introduce another layer at the Z zero location in the G code. The Creation Workshop slicer automatically positions the printer’s first layer at the step height for the rest of the print. In the case of catheter printing, this means that the first layer of the print is cured at a height of 20 microns.

Since the printer operator has minimized the distance between the Teflon film and build plate at the Z zero height, the first layer will be more successful if it is cured at this height. Therefore, the first layer of the print is copied and the height command is set to ‘Z0.0’ instead of ‘Z0.020’. An example of the G code commands required for a print is shown in section 6.4.

2.8.2 Exposure times

Another manual G-code edit is introduced with a tapered exposure time decrease throughout the first 5-10 layers. The first layer of a print is overexposed significantly to achieve strong adhesion to the build plate. Subsequent layers are exposed for less and less time until the optimal cure time for the material is reached.

The first layer is usually adhered with an 80 second exposure time. If a material needs more exposure time than this, it is likely that the distance between the Teflon film and build plate is greater than the penetration depth of the UV light. In this case, the Z zero may need to be adjusted or the Teflon film may require more tension to reduce film separation caused by viscous materials.

Additionally, the power setting of the UV projector can be increased to increase light penetration depth. If the projector is set to a high power the light penetration depth will increase, but so will the area of material cured. Low power is desirable for high-resolution printing since it does not cure material outside of the projected image due to stray light. However, the power setting must be high enough to penetrate the depth of the print layer height. Power settings as low as 80 (out of 255) have been proven successful with bulk matrix prints without fibers. However, higher power settings are usually required for high fiber volume fraction prints which do not allow as much light through the material.
The taper rate that has been most successful has been halving the exposure time for each layer until the regular layer exposure time is reached. Starting exposure time at 80 seconds, the next layer will be exposed for 40 seconds, then 20 seconds, etc. until the exposure time is reached.

2.9 New material calibration

Each time a new material is printed, the exposure times for the desired layer height must be determined. This is done with a small test print with 3 walls of varying widths to evaluate the accuracy of the print compared to the designed CAD file. These test prints are shown in Figure 28. The width of each wall is measured, then compared to the CAD file. If the walls are significantly wider than the design, the exposure time is too high. If the walls are too thin, the exposure time is too brief.

![Figure 28: Calibration prints. The wall thickness of three printed walls is measured and compared to the designed thickness in order to evaluate exposure times used when printing new materials.](image)

3 Material testing and selection

3.1 Bulk polymer testing

In order to produce catheters that give comparable results to commercially available products, the material properties of the printing matrix should closely match those of the polymers used in current neonatal catheters. Current neonatal catheters are commonly made of polyurethane and silicone blends. These materials are strong, yet flexible and enable catheters to bend around turns in the body without causing the patient discomfort.

UV curable silicones are not common in industry, and the few products that are manufactured are cost-prohibitive for this phase of material testing. Instead, different ratios of polyurethane (EBECRYL 8210), diacrylate (tetraethylene glycol diacrylate) and IBOA (Isobornyl acrylate) were tested in order to select a matrix material that would satisfy the comparative needs of this phase of testing.

Several polymer blends were functionalized with two types of photoinitiator – 1-Hydroxycyclohexyl phenyl ketone and Phenylbis(2,4,6-trimethyl-benzoyl)phosphine oxide – in
order to be UV curable. These photoinitiators activate cross-linking of polymer chains when exposed to UV light, solidifying the material into a cured part.

Each sample was cast and cured on the 3D printer, and then mechanically tested. A small amount (<1mL) of the uncured polymer was deposited in the center of the build tray. The Z axis was then homed, and the sample was cured at full projector power for 1 minute. The thin cured film was then removed from the build plate and post cured in the projector’s full power UV light for 2 minutes.

Dogbone samples of ISO 527-2 1BB standard were punched out of the polymer film with a standard dogbone die for tensile testing. At least five dogbones of each polymer blend were tested on an Instron machine. This machine regulates stress vs. strain measurements based off the standard dogbone size and an input measured sample thickness.

Each sample’s data points were averaged into one average stress vs. strain curve for that material. Each polymer blend’s data is shown in Figure 29: Stress vs. Strain curves for polymer matrix testing. The abrupt break points in the curve represent the strain at rupture of one of the samples averaged. After a sample failed it was taken out of the curve averaging data in order to get a more complete picture of the curve. However, it is important to note that the strain at rupture represented by the end of each curve indicates the highest-performing sample for each material, not the average strain at rupture.

A few basic conclusions can be made from these curves. First, the IBOA significantly increases the material’s Elastic modulus, as indicated by the steep slope of the ‘30PU 70IBOA’ sample.
Additionally, the IBOA significantly increases the strain at rupture, which is not pictured on the graph but was an average of about 500%.

The diacrylic constituent does not present a distinct relationship with strength properties based on its volume fraction. Instead, its material properties change dynamically with the complimentary volume fractions of polyurethane and IBOA.

Increasing the polyurethane volume fraction seems to decrease the elastic modulus but increase the strain at rupture based on a comparison of ‘40PU 45IBOA 15DA’ and ’30 PU 55IBOA 15DA’. However, this observation is also a part of a dynamic system, since the volume fraction of IBOA also changed between those two samples.

Based on the overall results, the blend of ‘30PU 55IBOA 15DA’ was selected for further testing because of its combination of ideal elastic modulus and ductility. The stress vs. strain curve of this material most closely matches that of the polyurethane blends shown in Figure 30, which are close to the material used in current neonatal catheters.

![Figure 30: Stress vs Strain of Polyurethane blends. Used as a reference only. [17]](image)

This material blend will be used as the polymer matrix in all future testing of catheters during this phase of the project. While it was the best material we tested, the matrix material should be revisited in greater detail in future phases of the project. During this phase of the project the focus will be on comparative results between reinforced parts and the bulk matrix. This enables the evaluation of different reinforcement types with respect to each other and a control, while still behaving similarly to a standard catheter matrix.

However, the material properties of this bulk catheter matrix are not nearly as strong as commercial catheter samples. The differences are clear based on qualitative observation of polyurethane neonatal catheter samples compared to the printed samples. In order to take full advantage of fiber reinforcement technology using 3D magnetic printing, the bulk matrix must have comparable mechanical properties to commercial properties so that fiber reinforcement can create a better end result than current commercial products.
3.2 Calcium Phosphate fiber reinforcement

3.2.1 Calcium Phosphate fiber properties

Calcium Phosphate was selected as the reinforcement fiber in catheters primarily due to its biocompatibility. The surface of these fibers can be magnetized with trace amounts of Iron Oxide particles and are safe to put into the body. [18] [12] The iron oxide particles used to magnetize the fiber can be seen on the surface of a CaP fiber in Figure 31. These strong ceramic fibers will reinforce the bulk catheter matrix based on their alignment direction.

![Figure 31: SEM image of magnetically-coated CaP fiber. Iron oxide nanoparticles on surface actuate magnetic response to applied field.](image)

3.3 Fiber alignment dynamics

When a magnetic field is applied to a magnetized fiber, it will create a magnetic torque that aligns the fiber along the direction of the magnetic field. Fibers with one long axis like Calcium Phosphate are referred to as rods. These rods require a static magnetic field to create a magnetic torque that aligns the rod in the applied field direction.

As a particle is aligning, viscosity has a significant effect on the alignment time. If the fluid that a fiber is in has a high viscosity, the fiber’s rotation opposed by high viscous torque. This effect allows for fast fiber alignment in low-viscosity fluids and creates long alignment times in high-viscosity fluids.

The dynamics of fiber alignment using magnetic fields are well-understood, and have been previously published. [13] Using the equations from this research, MATLAB simulations can be used to simulate fiber alignment times based on fiber size, viscosity and magnetic field strength. The MATLAB simulation is based on the following set of equations, where \( \mu_0 \) is the magnetic permeability of free space, \( \chi_{ps} \) is the volume susceptibility of the fibers, \( m \) is the mass of the fiber, \( A \) is the long axis length, \( d \) is the diameter of magnetic nanoparticles, \( B \) is the width of the
fiber, $H_0$ is the magnetic field strength, $\varphi$ is the angle between the applied magnetic field and the fiber, $p$ is the aspect ratio of the fiber, $S$ is the viscous torque constant, $T_{mag}$ is the magnetic torque, $T_n$ is the viscous drag torque and $I_O$ is the fiber’s inertia.

\[
T_{mag} = \frac{4\pi \mu_0 X_p s^2}{3(X_p s + 2)} [(A + d)(B + d)^2 - AB^2]H_0^2 \sin \varphi \cos \varphi \quad (17)
\]

\[
S = \frac{2}{A\sqrt{1-p^2}} \ln \left( \frac{1+\sqrt{1-p^2}}{p} \right) \quad (18)
\]

\[
\frac{f}{f_0} = \frac{4(1-p^4)}{3p^2(a^2-2-p^2)+2} \quad (19)
\]

\[
T_n = -6nV \frac{f}{f_0} * 4.3 \quad (20)
\]

\[
I_O = \frac{5}{m(A^2+B^2)} \quad (21)
\]

\[
\frac{d^2\varphi}{dt^2} = I_O(T_{mag} + T_n) \quad (22)
\]

Alignment times of CaP fibers in variable viscosities with the DLP printer’s magnetic field are plotted in Figure 32. The fibers are modeled as 50 microns long and 3 microns wide. The magnetic field strength modeled is the 3A field strength of 135 G.

\[\text{Numerical Solution of Fiber Alignment with Different Viscosities}\]

Figure 32: Alignment time of CaP fibers in varying viscosities. Higher fluid viscosities significantly slow alignment time.
By measuring the amount of time that it takes a fluid to cross a fixed distance through a glass pipe with a controlled diameter, the fluid’s viscosity can be calculated. This test yielded a fluid viscosity of 246.8 cP (Centipoise). Based on the results in Figure 32, it will take nearly 5 minutes to align these fibers at this field strength.

To investigate the effect of increased field strength on alignment times, alignment times were simulated at the experimental viscosity of approximately 250 cP with different field strengths at different applied currents, as labeled. The field strength of the same current with the modified extended core design outlined in section 2.2.2. The new DLP design will cut alignment times in this system in half, while similar results could be achieved in the current system by running the solenoids at about 5A.

Figure 33: Alignment time of 5% volume CaP fibers at varying field strengths. The magnetic flux density applied significantly affects alignment times.

3.4 Bulk composite testing

3.4.1 Sample procurement

In samples with 5% and 10% volume fraction of CaP fibers to matrix material were cast. A magnetic field of about 135 Gauss was applied to each sample for a duration of 2 minutes in the printing reservoir. The samples were then cured in the same method outlined in section 3.1. Dogbone samples were then punched out of the cured film. Since the alignment of fibers makes their mechanical properties anisotropic, the orientation of the dogbone being punched from the sample was critical to results. 5 samples of each volume fraction were punched at orientations of 0° alignment, with fibers oriented along the dogbone’s long axis. 5 other samples were punched...
with 90 ° alignment, with fibers aligned perpendicularly to the dogbone’s long axis. Punched samples from a cast film are shown in Figure 34.

![Figure 34: Punched dogbone samples of reinforced bulk material. Samples were punched with parallel and perpendicular fiber alignment for tensile testing.](image)

3.4.2 Tensile testing results

These samples were then tested and evaluated in the same method described in section 3.1. The results are plotted in Figure 35. The control plotted is the bulk matrix stress vs. strain curve that was previously tested in section 3.1.

![Figure 35: Stress vs. Strain of CaP reinforced bulk samples. Reinforced, aligned samples perform significantly better.](image)

These results clearly demonstrate an improvement in mechanical properties when aligned CaP fibers are introduced to the matrix. All samples outperformed the control matrix in terms of yield strength, yield point and tensile strength without a significant decrease in ductility, as indicated
by the high strain at rupture. Quantitative measurements based off these data are plotted with standard deviations in Figure 36 through Figure 39, with average data presented in Table 5.

Figure 36: Elastic modulus data for CaP reinforced samples. Parallel aligned samples perform significantly better than perpendicularly aligned samples.

Figure 36 clearly demonstrates an increased elastic modulus with increased fiber content. The higher the CaP volume fraction, the higher the sample’s elastic modulus. Additionally, it is clear that the fiber alignment direction significantly affects the elastic modulus. Aligning fibers along the dogbone’s long axis increased the elastic modulus by 38% and 26% when compared to perpendicular alignment for the 5% and 10% volume fraction samples, respectively. As a result, although the ‘5%, 0°’ sample demonstrates a higher elastic modulus than the ‘10%, 90°’ sample even though it has half of the CaP fiber volume fraction of reinforcement.

Figure 37: Yield point data for CaP reinforced samples.

Figure 37 demonstrates a significant increase in yield point at 10% strain for samples with higher CaP volume fractions. Additionally, a strong correlation between the alignment direction and yield point was demonstrated. Samples with fibers aligned along the long axis of the dogbone had yield points 33% and 24% higher than perpendicularly-aligned samples at 5% and 10% CaP fiber volume fraction, respectively.
Figure 38: Tensile strength data for CaP reinforced samples. Aligned composites have comparable tensile strength to the control. This indicates that material failure is still defect-driven by imperfect manufacturing.

Figure 38 shows a slight increase in tensile strength for reinforced samples. The ‘10%, 90°’ sample demonstrated the maximum tensile strength increase of 10%. While there is a clear pattern of tensile strength increase with fiber volume fraction and reinforcement angle, it is not nearly as significant as the increase observed in elastic modulus and yield point. This is due to the coupling of tensile strength properties with ductility in these samples.

In Figure 35, it is qualitatively apparent that these samples do not exhibit any necking behavior, where the stress in the sample is reduced after a certain strain where the tensile strength is reached. Since these samples do not undergo necking, their tensile strength is also the stress at rupture. Although the stress at the same strain is much higher for reinforced samples, samples with weaker reinforcement are more ductile and therefore last until a higher strain at rupture, as shown in Figure 39. This ductility results in a higher tensile strength for these samples, which significantly reduces the difference in tensile strength between the samples.

Table 5: Tensile testing average results
<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>5%</th>
<th>5%</th>
<th>10%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E</strong></td>
<td>35.74</td>
<td>51.08</td>
<td>70.64</td>
<td>64.02</td>
<td>80.93</td>
</tr>
<tr>
<td>StDev</td>
<td>3.29</td>
<td>5.08</td>
<td>6.28</td>
<td>4.33</td>
<td>2.46</td>
</tr>
<tr>
<td><strong>Strain</strong></td>
<td>108%</td>
<td>102%</td>
<td>91%</td>
<td>97%</td>
<td>81%</td>
</tr>
<tr>
<td>StDev</td>
<td>9%</td>
<td>8%</td>
<td>16%</td>
<td>10%</td>
<td>17%</td>
</tr>
<tr>
<td><strong>Yield</strong></td>
<td>2.37</td>
<td>3.24</td>
<td>4.31</td>
<td>3.99</td>
<td>4.94</td>
</tr>
<tr>
<td>StDev</td>
<td>0.17</td>
<td>0.27</td>
<td>0.30</td>
<td>0.24</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Tensile</strong></td>
<td>8.90</td>
<td>9.23</td>
<td>9.44</td>
<td>9.52</td>
<td>9.76</td>
</tr>
<tr>
<td>StDev</td>
<td>0.87</td>
<td>0.91</td>
<td>1.06</td>
<td>1.04</td>
<td>1.20</td>
</tr>
</tbody>
</table>

These results indicate some promise for the goal of this grant (6.1); to increase material strength in order to increase the inner diameter of neonatal catheters to allow for increased flow of drugs to the patient. While these tests do not directly address some mechanical properties—such as kinking, burst pressure and fluid flow—they suggest that these properties can be controlled by tuning CaP fiber alignment in a catheter.

### 3.4.3 Fiber alignment analysis

This observation is supported by the fiber alignment analysis results in Figure 33, which indicates that fiber alignment would take nearly 5 minutes at the measured fluid viscosity. The MATLAB model for fiber alignment times was used to drive the applied alignment time for this experiment, but the fiber length and viscosity were both improperly measured.

The samples were characterized using SEM for alignment success. Cross sections of each sample were taken using freeze fracturing after cooling in liquid nitrogen. Figure 40 shows alignment in a CaP cross section. The samples do show some degree of alignment, but it is difficult to make conclusive determinations about the average degree of alignment in the sample due to the ribbon-like characteristics of Calcium Phosphate fibers, as shown in Figure 41. Since the fibers are not perfectly cylindrical, errors are difficult to characterize statistically. However, the sample in Figure 40 does suggest that alignment was not entirely homogenous in the dogbone samples tested.
3.5 Catheter testing

3.5.1 Material selection

Based off the results of section 3.4.2, it is clear that 5% volume of CaP reinforcement in the catheter matrix is enough to demonstrate a distinct improvement in mechanical properties from the control. Since alignment times will increase as fiber content increases, printing with higher volume fraction samples will take significantly more time than lower volume fraction samples.

Additionally,
3.5.2 General catheter design

The nature of 3D magnetic printing introduces complications to the orientation of catheters produced using this geometry. Catheters may either be oriented vertically with axes normal to the build plate, or horizontally with axes parallel to the build plate. Printing vertically will enable close packing of adjacent catheters and high throughput per print as shown in Figure 42. Additionally, the final product would have a perfectly circular cross section that closely represents the geometry of a commercial product. However, these prints would require hundreds of layers to manufacture a 5cm-long catheter.

![Figure 42: Vertically-oriented catheters. High aspect ratio of prints will increase error with flexible printing matrix material.](image)

On the other hand, printing catheters horizontally introduces some pixilation error in the cross section of the catheter. Since each layer is sliced along the cross section of the part, the part’s cross section in the Z direction will not be perfectly circular. If the Z layer height is set high, then this pixilation will be significant. However, at 20-micron layer heights, the pixilation is small enough to not significantly affect the catheter’s cross section. Figure 43 shows catheter profiles that were printed horizontally on the build plate.

![Figure 43: Printed catheters without CaP fibers](image)
There are a few advantages of printing catheters horizontally. The time to print catheters is fairly low since printing time is primarily related to the Z height of the part. Although not as many catheters will be made per print as a vertically-oriented print, the overall time per catheter is likely comparable since the horizontal prints are much shorter, as shown in Figure 44. For complicated reinforcement geometries like the concentric or radial fiber orientation, prints will be much shorter when done horizontally. In a vertically-oriented print, each layer would have to be sliced into 12 magnetic alignment zones to achieve 12 alignment tolerances within ±15° of the actual alignment direction. Magnetically aligning in 12 different directions per layer would add significant print time, compared to incrementally changing the alignment direction as the catheter cross section changes throughout a horizontally-oriented print.

![Figure 44: Horizontally-oriented catheters with raft. Low aspect ratio of horizontal orientation improves print accuracy.](image)

Additionally, with these factors in mind, all catheter samples produced for testing have been oriented horizontally in the printing plane. A few printing limitations have been taken into consideration when designing the prints for French 4 catheters. In order to print a circular cross section normally to the build plate, some support structure must be implemented. The first layer of the print must be overexposed in order fully adhere to the build plate, as outlined in section 2.8.2. Therefore, the first layer of the print will not geometrically match the CAD model that was sliced.

Experiments
3.6 Catheter design for specific test procedures

As outlined in the grant for this research (6.1), a total of 5 tests will be used to evaluate fiber reinforcement geometries in the catheters. These include tensile breaking force, burst pressure, suction, static flow and kink testing. For each test, the catheters will be modified to accommodate fixtures to interface with testing equipment.

3.6.1 Tensile testing design

In

Two thicker flanges were designed onto both ends of the catheter. These flanges accommodate 1mm dowel pins in their center. This pin-in-flange design serves as a clamping point to reduce stress concentrations. Additional thickness is added to the flange wall to ensure that it is not the weak point in the catheter. The flange wall is gradually tapered down to the French 4 catheter cross-section. This design is shown in Figure 45. The length of the catheters tested was reduced from 5cm to a 1.5cm French 4 testing length. Since the Instron equipment normalizes for stress vs. strain, the length of a sample should not affect its result.

![Figure 45: CAD design of catheter for tension testing. Flanges will be clamped around a metal dowel pin to reduce stress concentration. Sample will fail in thin section.](image)

The

Once

3.6.2 Flow testing design

It

This test will involve measuring the volumetric flow rate of deionized water through the catheter. Each sample’s flow rate will be measured in mm³/min under a controlled hydrodynamic pressure head. Luer lock syringe tip fittings will be used to adapt from the water tank to the catheter. A 16-gauge syringe tip was selected since it is larger than the inner diameter of the catheter. A flange was designed onto one end of the catheter in order to receive the outer diameter of the
syringe tip. The catheter will be clamped around the syringe tip using some sort of zip tie or elastic band to provide compression and prevent the catheter from sliding off the syringe tip. A printed flow test catheter is shown in Figure 46.

![Flow test catheter](image)

**Figure 46: Flow test catheter. Syringe tip interfaces with liquid bath. Flow rate under constant hydrostatic pressure is measured.**

3.7 **Catheter post-processing**

In Figure 47: Printed catheters on base sheet. Small layer height results in circular cross section.

![Printed catheters](image)

**Figure 47: Printed catheters on base sheet. Small layer height results in circular cross section.**

First, the catheters are rinsed in an IPA bath diluted with 30% water for under 10 seconds. This is enough time to get the bulk of excess material off the catheters without affecting the matrix’s material properties. If the catheters are rinsed in the bath for too long, they will absorb some of the IPA solution and become bloated. This absorption makes the catheters weak and often causes part failure. This process may be repeated until the catheters have no more remaining uncured material inside or outside of their cross-sections. If trace amounts of fluid remain on the interior of the catheter, they will often form clots over time via capillary action, as shown in Figure 48.
First, the catheter must be removed from first layers of the print. As shown in Figure 47, the catheters are all attached to a base sheet from the overexposed first layer of the print. The exacto blade should be angled downwards against this sheet to easily remove the raft from the base material throughout the length of the catheter. After this process, the catheter and raft will be separated from the base of the sheet. The goal is to remove the catheter’s raft at the catheter’s tangent point without causing stress on the part or cutting into the catheter itself.

4 Direct-write magnetics design

4.1 Introduction to design

The

The

Three

4.2 Magnetic control system design

4.2.1 Initial design

The original magnetics design used a full core that was extended towards the printing plane with a tapered tip. This design is shown in Figure 49. The core design of these solenoids enabled a field increase of 12 times at the printing location compared to not having a core material. Additionally, high-resolution control over fiber alignment direction was demonstrated at the printing location under microscopic observation.
In order to investigate this effect, FEMM software was used to evaluate the magnetic field properties of the extended tapered core design. The axisymmetric model shown in Figure 50 provides a visualization of field error at the edge of the tapered core. While the field direction along the neutral axis of the solenoid is tightly controlled and superimposes properly, the field direction at the corner of the tapered solenoid is nearly perpendicular to the direction at the extrusion location. Since the magnitude of the flux density at the corner is comparable to the magnitude of the flux density at the extrusion location, significant realignment is introduced with this design.

While alignment is possible with tightly controlled viscosity parameters in an extrusion process using this design, the rate of material curing would have to be unreasonably rapid to cure extruded material before it left the alignment zone’s tolerance radius as shown in Figure 51. Prints would be prohibitively slow and this magnetic control system would not be scalable to any feasible application.
Figure 51: Alignment parameters of current direct-write printer design. Fibers must be aligned and cured before they leave a tolerance radius around the extrusion location.

4.2.2 Partial core design

The preliminary axisymmetric models indicated some level of validity to this concept. Figure 54 is a plot of the magnitude of flux density along the red line shown in Figure 53. There is a clear decrease in flux density outside moving radially away from the solenoid’s axis. However, the decrease is not abrupt enough to disregard misalignment issues altogether.

Figure 52: Partial core FEA model. Top blue line represents central axis of solenoid. Blue regions define separate materials.

Figure 53: Partial core FEA results. Lines represent field direction and color darkness represents flux density.
Figure 54: Flux density magnitude measured radially from axis of partial core, 1mm distance from core. Flux density peak near axis indicates promise for partial core design.

If the flux density is measured closer to the partial core, the field strength drops off more abruptly than in Figure 54. In Figure 55, the field strength drops off by 75% within about 3.5mm, compared to 5mm when measured at twice the distance from the core. This indicates that the partial core concept will be more effective when the cores are positioned closer to the printing plane. These preliminary results were promising enough to move onto more in-depth FEA of core designs that would be applied to the printer.

Figure 55: Flux density measured radially away from partial core axis, 0.5mm distance from core. Proximity to partial core significantly increases flux density peak.
With these promising results, more detailed FEA models were evaluated. The cylindrical partial core ends up creating a field spike that could cause realignment where the lower corner of the core comes in close contact with the printing plane. To combat this, a tapered tip was designed into the core. This tapered tip means that the core will be equidistant from the printing plane in the alignment zone. To represent the printing plane, measurements were taken on a line 35.1˚ from the solenoid’s axis, as indicated by the red line in Figure 56. This measurement line was standardized for all core designs that were tested.

![Figure 56: Tapered partial core. Red measurement lines represent printing plane in axisymmetric model. Tapered design maintains constant distance between core and printing plane.](image)

Several core design concepts were modeled in FEA. A chamfered core resulted in a distinct flux density spike, however this spike was not centered around the extrusion location. The graph in Figure 57 shows the flux density and error angle of Figure 56 centered around the extrusion location in the printing plane. From this graph, it is clear that the flux density peak is offset from the extrusion location towards the edge of the tapered core. Since the error angle is high at this location, this flux peak will cause fiber misalignment.

![Figure 57: Flux density and error angle of axisymmetric chamfered partial core. Flux peak is distinct, but offset from core’s axis at a high error location.](image)

In order to reduce the effects of fiber misalignment, the peak of flux density should be at the extrusion location, and the extraneous field directions should be significantly weaker. Without 3D FEA magnetics software it is difficult to evaluate more complex core designs that may satisfy these needs. However, 2D axisymmetric models were spliced together in order evaluate an
angled core design as shown in Figure 58. By splicing the measurements of one side of the printing plane in one half of the design with the other side of the printing plane in the other half of the design, the flux density for this design is simulated.

Figure 58: Combined FEA models of angled core tip. Spliced FEA models maintain constant offset distance between core and printing plane on both sides of the solenoid’s axis.

Figure 59: Interpolated flux density and error angle of angled partial core. Discontinuity exists at axis due to splicing of separate axisymmetric models. However, the model appears to have a strong flux peak at the solenoid’s axis. Flux angle exhibits high error at some parts of this location.

The results in Figure 59 show an improvement in the center point of the flux density’s peak. However, it is clear that the FEA model has a discontinuity near the neutral axis of the solenoid due to the splicing method of modeling. It is likely that the downwards spike in flux density between the spliced models makes a more continuous bell curve in a 3D model.
4.2.3 Design feasibility

Given

Although no industry standards for viscosity are published, experimental results suggested that corn syrup was viscous enough to hold its form after extrusion. The alignment dynamics of a minimum viscosity fluid will be evaluated using the higher range of viscosity for Karo corn syrup, 3000 cP [19]. The second-order differential model presented in section 3.3 is used to calculate the magnetic flux density required to align discontinuous carbon fibers in a reasonable amount of time for FDM printing.

Figure 60 shows the time required to align 30-micron discontinuous carbon fibers under different magnetic field strengths in a 3000 cP fluid. At the magnetic control system’s current field strength of around 250 Gauss, the alignment time is about 600 seconds, which is not feasible for any extrusion-based printing. In order to reduce the alignment time below 20 seconds, a field strength of nearly 1500 G is required. A field strength of 2000G reduces the alignment time below 10 seconds, which is a reasonable alignment time for some large-scale 3D printers.

![Numerical Solution of Magnetic Torque with Different Viscosities](image)

Figure 60: Fiber alignment times at 3000cP for extrusion-based additive manufacturing. Magnetic field strengths must be increased by an order of magnitude in order to achieve alignment times below 10 seconds.

To

Mathematical modeling was used in order to determine the solenoid size required to reach a field strength.
The equation shown in Figure 61 is used to measure the magnetic field strength along the axis of the solenoid, where $B_t$ is magnetic flux density, $\mu_0$ is the magnetic permeability of free space, $k$ is relative magnetic permeability of the core material, $r_1$ and $r_2$ are the inner and outer radii of the solenoid, respectively, $x_1$ and $x_2$ are the distances from the near and far face of the solenoid, respectively, $I$ is the current, and $n$ is the turn density per unit length. [20] This equation was used to model the magnitude of flux density as the dimension $r_2$ increases. As the solenoid’s outer radius increases, $x_1$ will also have to increase in order to stay above the printer’s clearance plane. This adjustment is included in the model. Although the aspect ratio of the solenoid changes when only $r_2$ is adjusted, this model gives a good preliminary understanding of the flux density limitations of this model. 

$$B_t = \frac{k\mu_0 I n}{2(r_2 - r_1)} \left[ x_2 \ln \frac{\sqrt{r_2^2 + x_2^2} + r_2}{\sqrt{r_1^2 + x_2^2} + r_1} - x_1 \ln \frac{\sqrt{r_2^2 + x_1^2} + r_2}{\sqrt{r_1^2 + x_1^2} + r_1} \right]$$  \hspace{1cm} (23)

The plot in Figure 62 shows how flux density increases with the outer radius of the solenoid. While this increase is promising, it would likely be improved by proportionately increasing the...
solenoid’s other dimensions. Figure 63 shows a comparison between the model from Figure 62 and a similar model that was corrected for a constant solenoid aspect ratio, equal to the aspect ratios of the current direct-write solenoids. Alignment strength vs. wire length is an important model because, when wire gauge and current are controlled, it is directly comparable to the solenoid’s efficiency in $G^2/W$, which was previously discussed in section 2.2.4.

![Alignment strength vs. Wire length](image)

**Figure 63:** Alignment strength vs. Wire length of different magnetics models. Controlled aspect ratio makes more efficient use of increased wire length, which corresponds directly to increased power.

While it is unreasonable to consider using 10 kilometers of wire for a solenoid to reach a flux density of 2000 G, larger gauge wires could significantly reduce the wire length required for these solenoids. Instead, looking at the solenoid’s overall dimensions helps give an understanding of the feasibility of implementing these solenoids on a printer. The current running around a solenoid can be controlled as a current flux ($A/m^2$) based on the wire gauge.

The overall dimensions of a solenoid creating a field strength of 2000 G would be a 246mm inner diameter, 450mm outer diameter and 360mm length. The FEA model in Figure 64 confirmed the legitimacy of these mathematics, measuring a 2041 G field at the printing location modeled.

![FEA model](image)
At this size, each solenoid would weigh about 359 kg, which is an unreasonable amount of weight to be placing on a moving 3D printer extrusion nozzle. Additionally, the power required to run each solenoid would create significant operational cost. Based on the sheer size of the solenoid required to align fibers in a fluid with 3000 cP viscosity, the orthogonal solenoid design is feasible only for large scale FDM printers with wide diameter filament. If a liquid cooling system were implemented, this field strength may be feasible with smaller solenoids due to increased current flux through the solenoid.

4.3 Next steps

While this orthogonal solenoid design is unlikely to be feasible for use in traditional FDM printing at a small scale, it may be feasible to implement in large scale industrial-sized printers. If the filament diameter is large, it can be used to quickly manufacture larger parts.

The aspect ratio that was controlled throughout the model in Figure 63 was arbitrarily determined. Although this provided a clearer metric of solenoid size vs. field strength, the aspect ratio could likely be optimized for higher flux density at the same wire length, and therefore power required to run the solenoid.

Additionally, the cooling in the current magnetic control system is a significant limiting factor. If this printer is to function with highly-viscous fluids at a small scale, the field strength must be increased by passing more current through each solenoid. The compressed air cooling system that is currently used allows for passage of 3.3A through 10 layers of 24AWG wire. If a fluid cooling system was implemented to the magnetic control system, the solenoids could operate at significantly higher current loads without overheating. This would require a redesign of the current magnetic control system nest, but may yield promising results to move this project forwards.

Finally, 3D magnetic FEA analysis should be used to evaluate the effectiveness of the partial angled core concept. While experimental results and 2D FEA modeling have yielded some promising results, they have been far from conclusive. A 3D FEA model of this design should answer many lingering questions about this magnetic control system concept.

5 Conclusions

5.1 Progress to date

3D magnetic printing of composite materials is a promising method for improving the mechanical properties of current neonatal catheters. An appropriate UV-curable polymer matrix was selected as the best available material for this phase of testing. This blend of polyurethane,
diacrylate and isobornyl acrylate was selected due to its combination of elastic modulus, tensile strength and ductility.

While this polymer matrix will serve well for comparative studies between reinforcement geometries, it is significantly weaker than existing polyurethane materials. If 3D magnetic printing is to be used for commercial catheter production, the polymer matrix must be redesigned to more closely-match the existing mechanical properties of commercial polyurethane in order to gain the full benefits of composite catheters.

Bulk casting dogbone samples demonstrated promising results for improving mechanical properties with fiber alignment. 10% volume of aligned CaP in the control matrix more than doubled the samples’ elastic modulus. This increase came without a significant sacrifice to ductility. Strain at rupture decreased 25% compared to the control, which is a relatively small decrease compared to the increase in elastic modulus.

Some factors indicate that the 2-minute alignment time for the dogbone samples was not sufficient for full alignment of the fibers. Mathematical modeling suggests that the printer’s alignment times for this material are near 5 minutes. Additionally, the reduced mechanical benefit of alignment in the higher fiber concentration sample indicates that its higher viscosity may have reduced alignment success. Further experimental testing will be required to validate the alignment times required for aligning CaP fibers during printing.

The magnetic field strength plays a critical role in the alignment time required for reinforcement fibers. With nearly 70 aligned layers in a printed French 4 catheter, printing times become cost-prohibitive in the current system unless alignment times are decreased. It is not feasible to achieve faster alignment by reducing material viscosity without sacrificing material properties. Therefore, significant consideration was given to increasing the printer’s magnetic field strength.

FEA models suggest that extending the soft magnetic core material off the front and back of the solenoid will increase magnetic field strength by over 50%, which will reduce alignment times by over 50%. Since field strength improvements can have such a significant effect on alignment time, different magnetic field design concepts were investigated.

Primarily, U-magnets were modeled in FEA and compared to the existing magnetic field system. The U-magnet designs offer a significantly increased area-weighted alignment efficiency, which means that U-magnets are a promising magnetic design concept for improving magnetic field strength while also scaling up the size of the build area. A prototype U-magnet alignment system was fabricated and confirmed a large percentage of usable area between the tips of the magnet.

A wide range of variables must be taken into consideration in order to produce parts with accurate geometric features and precise control of discontinuous fiber alignment. The mechanics of the DLP printer must be accurately coordinated with magnetic alignment. The printer’s magnetic field direction control was automated with a DC magnetic control system. This allows
for integrated G-code control of the magnetic field applied in the reservoir which streamlines the printing process.

The printer’s Z axis must be tightly constrained to achieve repeatability between prints and the high tolerance required to produce neonatal catheters. Error in the printer’s Z axis was reduced by constraining its linear rods tightly. The printer’s reservoir system was upgraded to use a Teflon film tensioning system, which improves the peel mechanics of printed parts from layer-to-layer and reduces system maintenance.

The exposure times for different material solutions must be determined experimentally in order to achieve geometric accuracy of printed parts. A test printing procedure was standardized in order to evaluate the power and length of exposure time for new materials. Once these materials are characterized, magnetic control is easily integrated to the printing process.

The mechanical printer improvements, printing matrix characterization and printing process improvements outlined in this thesis have pushed 3D magnetic printing to a point where production of Calcium Phosphate-reinforced catheters will yield conclusive results about the optimal reinforcement architectures for maximizing the mechanical properties of catheters and improving fluid flow to neonatal patients. The preliminary results of reinforced polyurethane-like materials indicate that Calcium Phosphate will yield improved mechanics over bulk polymers.

### 5.2 Future work

As this project progresses and the optimal fiber alignment architectures are determined for composite catheter reinforcement, the manufacturing process for producing catheters should be reevaluated. If geometric complexity or fiber reinforcement complexity are required in the final product, then 3D magnetic printing is an ideal manufacturing platform. In a scaled up system, catheters may be produced at higher volume. Additionally, 3D printing offers the potential advantage of pre-programming curvature into the catheter based off the patient’s body. Preprogrammed curvature may increase patient comfort while decreasing catheter stress and kinking.

On the other hand, if geometric complexity is not required and fiber alignment geometries are straightforward, then composite catheter manufacturing may be improved with continuous extrusion processes. For example, achieving longitudinal fiber alignment in an extruded catheter is relatively straightforward with the implementation of a solenoid around the extrusion die. Additionally, extrusion manufacturing eliminates the complications of manufacturing with a UV-curable matrix. Commercial polyurethanes could be easily mixed with magnetized Calcium Phosphate fibers. A continuous extrusion process may enable a significant increase of a catheter’s fluid flow properties at low manufacturing and materials cost.
6 Appendices

6.1 N2 Biomedical grant strategy

6.2 DLP solenoid control code

6.2.1 SLASolenoidControlPrinter

#include <math.h>
using namespace std;

float sol[3][3] = {{1,0,0},{0,1,0},{0,0,1}}; //Inverse of solenoid unit vector matrix
float direc[3];
float percent[5];
int pwm[5];
int r1=3; int c2=1; int i;
float pVec[3]; float pD1[3]; float pD2[3];
int mode=0; int n=1;
int frequency=2; //alternating platelet frequency (Hz)
int switchTime=1000/frequency; //time for each alternating platelet signal
float v1[3]; float v2[3]; float V[3];
float randV[3]={random(20),random(20),0}; //Random vector for platelet cross products
float R;
int b;
float zScale=0.70966; //XY solenoid strength over Z solenoid strength
int pulseLength;
int pwmValue; int highError; int lowError; int ERR=10;

float current=3; // Amps
int pctPWM=round(current*255/6); //255=6A, 170=4A, 85=2A, 42.5=1A

// PWM Library
int X=10; int Y=20; int Z=30; int XYff=50; int YXff=40; //fiber library
int XY=100; int XZ=170; int YZ=150; int fP1=180; int fP2=160; //platelet library

// Solenoid Pins
// Scheme: {y1,x1,z1,y2,x2}
int H1[5]={4,6,2,10,8};
int H2[5]={5,7,3,11,9};
int L1[5]={24,26,22,30,28};
int pulsePin=12;

void setup()
{
  for(i=0;i<5;i++)
  {
    pinMode(H1[i], OUTPUT);
    pinMode(H2[i], OUTPUT);
    pinMode(L1[i], OUTPUT);
    pinMode(L2[i], OUTPUT);
  }
  byte pulsePin; //change to whatever input pin is used
  Serial.begin(9600);
  Serial.println(pctPWM);
}

void loop()
{
  pulseLength = pulseIn(pulsePin, HIGH); //0-2000 microseconds
  pwmValue = 0.1258 * pulseLength + 0.2863;

  // Interpret the pwmValue if it is different from the previous pwmValue
  if (pwmValue<lowError || pwmValue>highError)
  {
    interpret();
    n=0;
    Serial.println(pwmValue);
    highError=pwmValue+5;
    lowError=pwmValue-5;
  }

  // If the alignment direction has been updated, power solenoids
  if (n==0)
  {
    n=1;
    // If system is
    if (mode==9)
    {
      off();
    }
    // If system is in fiber mode
    if (mode==0)
{
    normalize();  
    convert(direc);  
    maximum();  
    power();
}

// If system is in platelet mode
if (mode==1)
{
    platelets();  
    convert(pD2);  
    maximum();  
    // power();  
    // delay(switchTime);  
    b=1;
}

// If system is in Platelet mode, alternate between normal pulsing vectors in intervals of switchTime
if (mode==1)
{
    if (b==1)
    {
        convert(pD1);  
        maximum();  
        power();  
        //Serial.println("90 degrees");  
        delay(switchTime);  
        b=2;
    }
    if (b==2)
    {
        convert(pD2);  
        maximum();  
        power();  
        //Serial.println("0 degrees");  
        delay(switchTime);  
        b=1;
    }
}
6.2.2 **Library**

// Compares PWM value with library
// Assigns alignment direction
// Assigns alignment type (Platelets: mode=1, Fibers: mode=0;
void interpret()
{
    if (-ERR<=pwmValue && pwmValue<ERR)
    {
        direc[0]=0;
        direc[1]=0;
        direc[2]=0;
        mode=9;
        Serial.println("OFF");
    }

    // Fiber library ///////////////////////////////////////////////////////////////////////////////////////
    if (X-ERR<pwmValue && pwmValue<X+ERR)
    {
        direc[0]=1;
        direc[1]=0;
        direc[2]=0;
        mode=0;
        Serial.println("X Direction");
    }
    if (Y-ERR<pwmValue && pwmValue<Y+ERR)
    {
        direc[0]=0;
        direc[1]=1;
        direc[2]=0;
        mode=0;
        Serial.println("Y Direction");
    }
    if (Z-ERR<pwmValue && pwmValue<Z+ERR)
    {
        direc[0]=0;
        direc[1]=0;
        direc[2]=1;
        mode=0;
        Serial.println("Z Direction");
    }
    if (XYff-ERR<pwmValue && pwmValue<XYff+ERR)
    {
        direc[0]=1;
    }
direc[1]=1;
direc[2]=0;
mode=0;
Serial.println("XY 45 Direction");
}
if (YXff-ERR<pwmValue && pwmValue<YXff+ERR)
{

direc[0]=1;
direc[1]=-1;
direc[2]=0;
mode=0;
Serial.println("XY -45 Direction");
}

// Platelet library /////////////
//XY-ERR<pwmValue && pwmValue<XY+ERR) //XY plane
{
    pVec[0]=0;
pVec[1]=0;
pVec[2]=1;
    mode=1;
    Serial.println("XY Plane");
}
if (XZ-ERR<pwmValue && pwmValue<XZ+ERR) //XZ plane
{
    pVec[0]=0;
pVec[1]=1;
pVec[2]=0;
    mode=1;
    Serial.println("XZ Plane");
}
if (YZ-ERR<pwmValue && pwmValue<YZ+ERR) //YZ plane
{
    pVec[0]=1;
pVec[1]=0;
pVec[2]=0;
    mode=1;
    Serial.println("YZ Plane");
}
if (ffP1-ERR<pwmValue && pwmValue<ffP1+ERR) //YZ plane
{
    pVec[0]=1;
pVec[1]=1;
pVec[2]=0;
mode=1;
Serial.println("+45");
}
if (ffP2-ERR<pwmValue && pwmValue<ffP2+ERR) //YZ plane
{
    pVec[0]=1;
pVec[1]=-1;
pVec[2]=0;
    mode=1;
    Serial.println("-45");
}
}

6.2.3 Platelets

// Establishes pulsing vectors for platelet alignment
// Sets pD1 and pD2 globally
void platelets()
{
    Serial.println("Platelets");
    xp1();
    xp2();
    normalizeP();
}

// Sets direction of pD1 based off pVec and random vector
float xp1() //sets direction of pD1
{
    pD1[0]=pVec[1]*randV[2]-pVec[2]*randV[1];
pD1[1]=-(pVec[0]*randV[2]-pVec[2]*randV[0]);
pD1[2]=pVec[0]*randV[1]-pVec[1]*randV[0];
}

// Sets direction of pD2 based off pVec and pD1
float xp2() //pD2 based off pD1
{
    pD2[0]=pVec[1]*pD1[2]-pVec[2]*pD1[1];
pD2[1]=-(pVec[0]*pD1[2]-pVec[2]*pD1[0]);
pD2[2]=pVec[0]*pD1[1]-pVec[1]*pD1[0];
}

// Converts pD1 & pD2 to unit vectors
float normalizeP()
{

float n1fact=sqrt(pow(pD1[0],2)+pow(pD1[1],2)+pow(pD1[2],2));
pD1[0]=pD1[0]/n1fact;
pD1[1]=pD1[1]/n1fact;
pD1[2]=pD1[2]/n1fact;

float n2fact=sqrt(pow(pD2[0],2)+pow(pD2[1],2)+pow(pD2[2],2));
pD2[0]=pD2[0]/n2fact;
pD2[1]=pD2[1]/n2fact;
pD2[2]=pD2[2]/n2fact;

} 

6.2.4 Power 

// Converts direc to unit vector
float normalize()
{
  float nfact=sqrt(pow(direc[0],2)+pow(direc[1],2)+pow(direc[2],2));
  direc[0]=direc[0]/nfact;
  direc[1]=direc[1]/nfact;
}

// Sets highest powered solenoid to max power, and adjusts other solenoids proportionally
// Maximizes field strength for alignment direction
void maximum()
{
  float maxi=abs(percent[0]);
  for (i=1;i<5;i++)
  {
    if (abs(percent[i])>maxi)
    {
      maxi=abs(percent[i]);
    }
  }
  for (i=0;i<5;i++)
  {
    percent[i]=percent[i]/maxi;
  }
}

void off()
{
  for(i=0;i<5;i++)
\{ 

  analogWrite(H1[i],0);
  analogWrite(H2[i],0);
  delay(200);
  digitalWrite(L1[i],LOW);
  digitalWrite(L2[i],LOW);
\}

// Converts power percentage to pwm output value
// Powers solenoids
void power()
{
  for(i=0;i<5;i++)
  {
    pwm[i]=round(percent[i]*pctPWM); //rounds to nearest pwm value
  }

  Serial.println("PWM:");
  for(i=0;i<5;i++)
  {
    if(percent[i]<0)
    {
      analogWrite(H1[i],0);
      digitalWrite(L1[i],LOW);
    }
    else
    {
      analogWrite(H2[i],0);
      digitalWrite(L2[i],LOW);
    }
  }
  delay(100);
  for(i=0;i<5;i++)
  {
    if(percent[i]<0)
    {
      digitalWrite(L2[i],HIGH);
      analogWrite(H2[i],abs(pwm[i]));
    }
    else
    {
      digitalWrite(L1[i],HIGH);
      analogWrite(H1[i],abs(pwm[i]));
    }
  }
}
6.3 Peel function code modifications

case 651: // M651 run peel move
{
    if(peel_distance > 0);
    {
        int peel_tracker = 0;
        int peel_first = 0;
        while(peel_tracker < peel_count)
        {
            peel_tracker++;
            if (peel_first == 0)
            {
                plan_buffer_line(destination[X_AXIS], destination[Y_AXIS], destination[Z_AXIS],
                                destination[Z_AXIS] + peel_skew * peel_tracker, peel_speed, active_extruder);
                peel_first=1;
            }
            else
            {

            }}
        }
    }
}
plan_buffer_line(destination[X_AXIS], destination[Y_AXIS], destination[Z_AXIS] + peel_skew * (peel_tracker - 2), destination[Z_AXIS] + peel_skew * peel_tracker, peel_speed, active_extruder);
plan_buffer_line(destination[X_AXIS], destination[Y_AXIS], destination[Z_AXIS] + peel_skew * (peel_tracker - 1), destination[Z_AXIS] + peel_skew * peel_tracker, peel_speed, active_extruder);
}
}
plan_buffer_line(destination[X_AXIS], destination[Y_AXIS], destination[Z_AXIS] + peel_distance, destination[Z_AXIS] + peel_distance, peel_speed, active_extruder);
st_synchronize();

6.4 Example G-code for print control

;********** Header Start ********
;Here you can set any G or M-Code which should be executed BEFORE the build process
G21 ;Set units to be mm
G91 ;Relative Positioning
G28 ; Home Printer
M650 D5.0 S0.5 P0;mUVe 1 Prefs - Start
M17 ;Enable motors
M280 S80 P0;
M140 S40;
;<Slice> Blank
;<Delay> 120000
;<Slice> Blank
;********** Header End ********

;********** Pre-Slice Start ********
G1 Z0
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********** Pre-Slice End ********
;<Slice> 0
;<Delay> 80000
;<Slice> Blank
;********** Lift Sequence ********
M280 S80 P0;
M106 S0;
G4 P100;
M651; Do mUVe 1 Peel Move
;********* Lift Sequence *********

;********* Pre-Slice Start *********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********* Pre-Slice End *********
;<Slice> 1
;<Delay> 40000
;<Slice> Blank
;********* Lift Sequence *********
M280 S80 P0;
M106 S0;
G4 P100;
M651; Do mUVe 1 Peel Move
;********* Lift Sequence *********

;********* Pre-Slice Start *********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********* Pre-Slice End *********
;<Slice> 2
;<Delay> 20000
;<Slice> Blank
;********* Lift Sequence *********
M280 S80 P0;
M106 S0;
G4 P100;
M651; Do mUVe 1 Peel Move
;********* Lift Sequence *********

;********* Pre-Slice Start *********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********* Pre-Slice End *********
;<Slice> 2
;<Delay> 10000
;<Slice> Blank
;********** Lift Sequence **********
M280 S80 P0;
M106 S0;
G4 P100;
M651; Do mUVe 1 Peel Move
;********** Lift Sequence **********

;********** Pre-Slice Start **********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********** Pre-Slice End **********
;<Slice> 3
;<Delay> 5000
;<Slice> Blank
;********** Lift Sequence **********
M280 S80 P0;
M106 S0;
G4 P100;
M651; Do mUVe 1 Peel Move
;********** Lift Sequence **********

;********** Pre-Slice Start **********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********** Pre-Slice End **********
;<Slice> 4
;<Delay> 2500
;<Slice> Blank
;********** Lift Sequence **********
M280 S80 P0;
G4 P100;
M106 S0;
;<Delay> 130
M651; Do mUVe 1 Peel Move
;********** Lift Sequence **********
;********** Pre-Slice Start **********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********** Pre-Slice End **********
;<Slice> 5
;<Delay> 1200
;<Slice> Blank
;********** Lift Sequence **********
M280 S80 P0;
G4 P100;
M106 S0;
;<Delay> 130
M651; Do mUVe 1 Peel Move
;********** Lift Sequence **********

{Repeated G code for missing layers}

;********** Pre-Slice Start **********
G1 Z.02
M106 S10; X alignment
;<Delay> 60000
M280 S15 P0;
G4 P200;
;********** Pre-Slice End **********
;<Slice> 158
;<Delay> 1200
;<Slice> Blank
;********** Lift Sequence **********
M280 S80 P0;
G4 P100;
M106 S0;
;<Delay> 130
M651; Do mUVe 1 Peel Move
;********** Lift Sequence **********

;********** Footer Start **********
;Here you can set any G or M-Code which should be executed after the last Layer is Printed
G90 ;Set back to absolute
G1 Z100;
M18 ;Disable Motors
M106 S0;
7 References


