Design and Control of Fiber Encapsulation Additive Manufacturing

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DESIGN AND CONTROL

OF

FIBER ENCAPSULATION ADDITIVE MANUFACTURING

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DESIGN AND CONTROL
OF
FIBER ENCAPSULATION ADDITIVE MANUFACTURING

A Dissertation Presented to the Graduate Faculty of the
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in
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by
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This work presents the design, development, and analysis of the Fiber Encapsulation Additive Manufacturing (FEAM) system developed at the Laboratory for Additive Manufacturing Robotics & Automation at the Lyle School of Engineering at Southern Methodist University. The innovation introduced by FEAM is the ability to insert a continuous fiber of different material into the flowing extrudate. Correctly positioning the fiber feed inside the extrudate while turning the fiber in arbitrary directions is a critical aspect of the technology. This will allow for the full exploitation of the capabilities of the FEAM technology to produce robotic components that actuate and sense. Several compensation strategies for fiber placement are proposed and implemented after recording and analyzing data to characterize the FEAM process. The FEAM technology consists of a tube that guides a coaxial fiber underneath the melt flow of a material extrusion based nozzle. The fiber has to be fed into the flow parallel to the path direction that is co-planar with the horizontal motions. To achieve this a the horizontal motion axes are mounted atop a rotary axes and synchronous motion between these three axes is programmed to maintain the direction. Once the fiber is underneath the melt flow, the extrudate flows around the fiber and encapsulates it as part of the freezing process. Due to the behavior of this process the fiber will end up off-centerline during certain printing configurations that include higher planar
velocities and small radii of curvature. A procedure to investigate this behavior is developed and used to quantify the phenomenon. The provided data informs several strategies to compensate in effort to accommodate higher process performance and wider range of design parameters in during printing. These strategies involve limiting angular velocity, anticipating the displacement by biasing the guide, and utilizing the rotary motion underneath the planar axes. Of these the most improvement to the FEAM process was observed in the guide biasing strategy, followed by the angular velocity ceiling. The rotary biasing of the guide against the planar direction had mixed results with no clear benefit.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................... ix
LIST OF TABLES ........................................................................... xiii

CHAPTER

1. INTRODUCTION ....................................................................... 1
   1.1. 3-D Printing and Additive Manufacturing ......................... 1
   1.2. Fiber Encapsulation Additive Manufacturing .................... 4

2. FEAM SYSTEM DESIGN .......................................................... 9
   2.1. Design of the FEAM Machine ............................................ 11
   2.2. Motion of the FEAM Machine .......................................... 15
   2.3. Prototype Components & Devices ..................................... 18

3. THE FEAM FIBER CENTERING PROBLEM ......................... 28
   3.1. The Output of Fiber Encapsulation Additive Manufacturing .... 28
   3.2. The Effect of Printing Parameters .................................... 30

4. EXPERIMENTAL SETUP ......................................................... 35
   4.1. Turn Radius .................................................................... 35
   4.2. Tangential Velocity .......................................................... 37
   4.3. Tangential Velocity .......................................................... 38
       4.3.1. Extrudate Heating .................................................... 38
       4.3.2. Fiber Heating ........................................................ 39
       4.3.3. Active Extrudate Cooling ........................................... 39

5. EXPERIMENTAL PROCEDURE .............................................. 41
   5.1. Measurement Technique .................................................. 41
5.2. Calculations ......................................................... 49
   5.2.1. Extrudate Calculation ................................. 49
   5.2.2. Wire Calculation ........................................ 51
5.3. Error Analysis .................................................... 52
   5.3.1. Systematic Errors ............................. 52
   5.3.2. Random Errors ......................................... 54
6. EXPERIMENTAL RESULTS ........................................... 57
   6.1. Uncompensated Results ................................. 57
   6.2. Error Compensation Strategies and Results .......... 63
      6.2.1. Maximum Angular Velocity Strategy, \( \omega_{\text{max}} \) .................. 63
      6.2.2. Compensatory Lateral Displacement, \( Y' \) Strategy .......... 68
      6.2.3. Over- and Under-Bending, \( \theta_b \) Strategy ............. 73
      6.2.4. Pre-Bending, \( \theta_b \) Strategy .................... 78
7. DISCUSSION & CONCLUSION ........................................ 82

APPENDIX

A. APPENDIX .......................................................... 90
   A.1. Semi-Automated Repeatability Results ................. 90
   A.2. Nozzle-\( \theta \) Stage Alignment .......................... 96
<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. X-Z plane schematic of the fundamental FEAM process. The arrow indicates build platform feed direction.</td>
<td>4</td>
</tr>
<tr>
<td>1.2. Isometric view of the $\theta - X - Y$ stage, kinematic mount and build platform.</td>
<td>5</td>
</tr>
<tr>
<td>1.3. SolidWorks CAD model of an idealized FEAM output: a copper wire encapsulated in a clear thermoplastic.</td>
<td>6</td>
</tr>
<tr>
<td>2.1. Horizontal View of the FEAM printer showing the main motion stages (X, Y, Z), the secondary guide stages (X', Y', Z') and the cutter feeder itself.</td>
<td>10</td>
</tr>
<tr>
<td>2.2. Detail view of the Cutter-Feeder mechanism.</td>
<td>13</td>
</tr>
<tr>
<td>2.3. Side and underside view of the Cutter-Feeder mechanism.</td>
<td>14</td>
</tr>
<tr>
<td>2.4. Block diagram showing the information, programming, and control flow of the FEAM printer.</td>
<td>16</td>
</tr>
<tr>
<td>2.5. Helical coils produced using the FEAM technology.</td>
<td>18</td>
</tr>
<tr>
<td>2.6. Speaker driven by a voice coil actuator positioned inside a commercial speaker magnet and attached to an audio amplifier.</td>
<td>20</td>
</tr>
<tr>
<td>2.7. Linear Variable Differential Transformer based off of 3 coaxial stacked helical coils.</td>
<td>21</td>
</tr>
<tr>
<td>2.8. Electrical junctions, both intra- (left) and inter-layer (right).</td>
<td>22</td>
</tr>
<tr>
<td>2.9. SMD devices are added to a combined FEAM and TEAM printed prototype. Schematic shown on the left, and prototype on the right.</td>
<td>22</td>
</tr>
<tr>
<td>2.10. Pushbutton produced by the FEAM process with flexible thermoplastic matrix.</td>
<td>24</td>
</tr>
<tr>
<td>2.11. A capacitive force sensor composed of 3 bulk extrudate layers with the inner layer being more compliant. Conductive plates are approximated with square wire spirals.</td>
<td>25</td>
</tr>
<tr>
<td>2.12. Monolithically printed solenoid with FEAM spiral coils, interlayer junctions, soft magnetic core, and PVA sacrificial material.</td>
<td>26</td>
</tr>
</tbody>
</table>
3.1. YZ plane view of the FEAM system. ........................................ 29

3.2. Top-view schematic showing an undesirable dynamical result of the
FEAM system. ........................................................... 31

4.1. Schematic of the Horseshoe pattern showing a 180° turn with vari-
ous constant radii of curvature. Additionally the test pattern
shows the three before control traces and the three after control
 traces. All of the channels have the same dimensions. Units
are millimeters. Dimensions are to the centerline of the traces.
Turnaround traces are supported by the pattern that extends
outside the rectangular region. ........................................... 36

4.2. Top-view schematic showing effect of turn radius shown in (a) a
 moderate turn radius, and (b) a small turn radius with failure..... 37

4.3. Top-view schematic showing location of the freezing font a distance
l from the nozzle. ....................................................... 40

5.1. Schematic showing the location of the centers of the microscope im-
ages as red dots. ............................................................ 42

5.2. Schematic describing the location of each of the microscope images. ..... 43

5.3. Schematic showing the print orientation of the continuous fiber within
a single specimen. The fiber starts at the segment at the bottom
right. The squares center-left do not contain fiber, and are used
for calibration of the extrudate position. .............................. 44

5.4. Composite of cropped microscope images showing the extrudate con-
trols (left), wire controls (top and bottom horizontals) and the
largest 0.75in radius horseshoe for the corresponding test specimen. 45

5.5. Microscope image showing the full image taken, and the cropped
zone indicated by the white box. The area of interest in this
image is entirely contained within the cropping box. ................. 47

5.6. Selected measurement locations for both an extrudate without a fiber
and an extrudate with a fiber. The locations are indicated by
black dots........................................................................ 48

5.7. Schematic of the coordinate system used for data extraction. ........ 49

5.8. Microscope camera alignment can result in errors in edge detection
on extrudate and fiber extents. .......................................... 52

5.9. Nozzle-θ axes misalignment can cause systematic measurement error,
which is shown in this top view of the build platform. ............... 53

6.1. Schematic of the numbering scheme for the Specimen Location num-
bers. ........................................................................... 58

6.2. Displacement of the extrudate from print centerline on the extrudate-
only specimens. ........................................................... 59
6.3. Displacement of the extrudate from print centerline on the extrudate 
and wire specimens. ........................................... 61
6.4. Displacement of the wire from print centerline on the extrudate and 
wire specimens .................................................. 62
6.5. Maximum Angular Velocity Strategy depicted in a top view of a 
single horseshoe. .................................................. 64
6.6. Tracking error vs. reference $\theta$ angle for each uncompensated speci-
men configuration. Angular velocity values are in rad/sec. Color 
shows $v_t$ and symbol shows radius. ............................ 65
6.7. Displacement of the extrudate from print centerline on the extrudate 
and wire specimens with $\omega_{max}$ compensation. ............. 66
6.8. Displacement of the wire from print centerline on the extrudate and 
wire specimens with $\omega_{max}$ compensation. ................. 67
6.9. $Y'$ strategy biases the position of the guide to compensate for man-
ufacturing errors. ................................................. 69
6.10. Illustration of the circular approximation of wire displacement vs. 
position on horseshoe. ........................................... 70
6.11. Displacement of the extrudate from print centerline on the extrudate 
and wire specimens with $Y'$ compensation. .................... 71
6.12. Displacement of the wire from print centerline on the extrudate and 
wire specimens with $Y'$ compensation. ......................... 72
6.13. Over- and Under-Bending strategy biases the $\theta$ angle of the guide 
relative to the path. ............................................ 73
6.14. Linear approximation for $\theta$ over/under bending used to approximate 
the error of the fiber position in the extrudate. .................... 74
6.15. Displacement of the extrudate from print centerline on the extrudate 
and wire specimens with $\theta_b$ compensation. .................. 76
6.16. Displacement of the wire from print centerline on the extrudate and 
wire specimens with $\theta_b$ compensation. ......................... 77
6.17. Pre-bending implementation (red) compared to the over- and under-
bending (pink and cyan.) ........................................ 78
6.18. Displacement of the extrudate from print centerline with $\theta_b$ Pre-
Bending compensation. ............................................. 80
6.19. Displacement of the wire from print centerline with $\theta_b$ Pre-Bending 
compensation. .................................................... 81
7.1. RMS error on extrudate vs. strategy applied. Error bars illustrate the range of variability within the specimen category. .................. 85

7.2. RMS error on wire vs. strategy applied. Error bars illustrate the range of variability within the specimen category. .................. 86

A.1. Standard deviation of extrudate extents vs. horseshoe position. ........ 91
A.2. Standard deviation of extrudate extents vs. horseshoe location. ........ 91
A.3. Standard deviation of extrudate extents vs. radius of curvature. ....... 92
A.4. Standard deviation of extrudate extents vs. angular velocity. .......... 92
A.5. Standard deviation of wire extents vs. position number. ............... 93
A.6. Standard deviation of wire extents vs. horseshoe location. ............. 94
A.7. Standard deviation of wire extents vs. radius of curvature. ............. 94
A.8. Standard deviation of wire extents vs. angular velocity. ............... 95
A.9. Procedure showing the planar path taken by the X and Y stages while rotating $\theta$ at a constant rate. .................. 97
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. Summary of In-Process Build Parameters and Properties</td>
<td>34</td>
</tr>
<tr>
<td>5.1. Average and sample standard deviation as a function of location on the horseshoe pattern for 5 immediately subsequent data extractions.</td>
<td>54</td>
</tr>
<tr>
<td>5.2. Average and sample standard deviation as a function of location on the horseshoe pattern for five subsequent days.</td>
<td>55</td>
</tr>
<tr>
<td>7.1. Manufacturing configurations and specimens grouped by compensation strategy.</td>
<td>83</td>
</tr>
<tr>
<td>7.2. Summary of specimen sets.</td>
<td>84</td>
</tr>
<tr>
<td>7.3. Summary of Results by Compensation Strategy on Extrudate</td>
<td>87</td>
</tr>
<tr>
<td>7.4. Summary of Results by Compensation Strategy on Copper Wire</td>
<td>88</td>
</tr>
</tbody>
</table>
for Jen
Chapter 1
INTRODUCTION

1.1. 3-D Printing and Additive Manufacturing

Additive Manufacturing is a large category of manufacturing processes that differ from traditional manufacturing such as milling, drilling, turning, etc., which remove material from a stock or precursor part. Instead material is added in succession until the desired part is produced. Additive manufacturing techniques allow for rapid prototyping, production of geometries not previously possible, and introduce entirely new applications [8, 76]. The earliest types of additive manufacturing consist of a combination Laminated Object Manufacturing (LOM)[39, 47, 52], Selective Laser Sintering (SLS)[5, 6, 15], and Fused Filament Fabrication (FFF, trademarked by Stratasys as Fused Deposition Modeling or FDM) [13, 14]. Every additive manufacturing technique consists of taking a 3-D representation of a desired object programmed into a computer model, and mathematically creating individual cross sections or layers. Each of these layers are produced subsequently through a variety of techniques. The layers are stacked on the previously produced layer until the full model is reproduced in a volume [83]. Originally the work part consists of one material. The inclusion of secondary sacrificial materials has been introduced to produce more complex structures including those of a biological nature [17]. Further advancing the capability of 3-D printing technology is the ability to use or produce application-specific composites. This is an area of active research distributed among a wide variety of techniques such as SLS, Laser Engineered Net Shaping, LOM, Fiber Reinforced LOM, Stere-
olithography (SL), Fiber Reinforced SL, and FFF [31, 78]. More recently researchers have been focusing on developing techniques to produce 3-D printed smart devices that contain active functionality by incorporating actuators and sensors as part of the model design and subsequent additive manufacturing process [35].

There are additive manufacturing techniques capable of producing parts made from highly electrically conductive materials [1], including electronic devices made by 3-D printing metals [22]. Potential applications of these kinds of printable devices include 3-D printed soft robots [38, 41], prosthetics [32], wearable electronics [74], embedded sensors [48, 62], and tunable prototypes [16].

However, to produce functional electronics and electromechanical devices the capability to co-deposit composites of insulators and conductors is required. Unfortunately electrically conductive materials typically require process temperatures much greater than what electrically insulating materials, commonly polymers, are compatible with. The incompatibility arises where the melting point of the conductive materials is far above the denaturing temperature of the non-conductive materials.

Current research on producing electronics via additive manufacturing processes utilizes traces of conductive inks [40, 63], including the printing of a silver ink electronic speaker [42], integration with biological materials [43], and ink-jet printing of silver ink [70]. Direct Ink Writing of a potentiostat sensor [19] is an example of these devices. The commercialization of 3-D printing technologies that can produce electronic circuitry is starting to be realized [3]. Limitations of silver based inks are the relatively high resistivity and cost of materials. This is a significant factor when comparing current carrying capacity to that of a copper wire or trace, which is readily available and commonly used as electrical conductors in electronics [45]. Improving current carrying capacity in additive manufacture of electronics is a factor of interest.
Copper has several significant advantages over many materials in terms of cost per resistivity. Cost per volume of copper can be two orders of magnitude lower due to its wide availability for use in circuits [60]. Other researchers have observed this advantage and have worked on solid conductor 3-D printing [27, 28, 34]. The Spool-Head project was designed to feed, place, bond, and cut a copper wire in a two-step process, swapping out a FDM style print head with a special heated-tip SpoolHead feeder [4]. The Multi3D system combines polymer extrusion, wire embedding, micromachining, pick and place, and micro-welding into a unified system [2]. The wire embedding is accomplished using ultrasonic excitation to re-flow the polymer matrix producing a composite as it freezes on the wire. In addition to the electrical advantages, these composites often have other mechanical benefits [23, 29] with multiple applications [21, 26]. Further research adapting FFF for continuous fiber printing via straight-through-nozzle fiber feeding is being developed [44].

Additional opportunities arise with soft robot manufacturing that is traditionally labor intensive [77], and would lend itself to the benefits of additive manufacturing [36, 59]. Moreover there are difficulties in utilizing already existing additive manufacturing techniques with softer polymers. Blindly attempting to use ultra-soft polymers in a FFF environment results in a buckling problem with the feed mechanisms [18, 20]. This creates additional challenges in utilizing these materials in processes that depend on a material phase change, as is the case in FFF. However, being able to overcome these challenges makes rapid production of a new class of applications [53, 55] and robots possible, including the potential for bio-inspired robotics [33], wearable robotics [30], 3-D printed bioimplants [25], and wearable sensors [37]. Additionally, robots that have soft sensors and actuators designed into the manufacturing process are possible [46, 85]. Additive manufactured sensors are of interest to researchers due to the numerous potential applications they enable such as 3-D printed sensors.
As the capability of 3-D printing technology improves, so will the potential for new types of designs and for increasingly complex devices that were not previously considered possible. Additionally, current developments in 3-D printing processes may lead to manufacturing processes foreseen by science fiction [57].

1.2. Fiber Encapsulation Additive Manufacturing

Fiber Encapsulation Additive Manufacturing (FEAM) is a technology that enables the rapid design and production of robotic components via 3D printing [7, 10, 11, 12, 40, 60, 61, 71]. At its core, the FEAM technology consists of inserting a coaxial fiber that is fed and positioned by a guide into the melt flow from a nozzle similar to the ones found in FFF printers. The extrudate then freezes over the fiber and locks the fiber in place. This allows for fiber traces to be insulated and placed in arbitrary directions, typically in a layer as shown in Fig. 1.1. The coaxial fiber contrasts with fiber-reinforced composites that have small fiber strands distributed as part of the

![Figure 1.1. X-Z plane schematic of the fundamental FEAM process. The arrow indicates build platform feed direction.](image-url)
bulk material filament [9, 68, 86].

In order to successfully position the fiber inside the extrudate, the fiber insertion direction has to be held tangent to the deposition path. The kinematics of the FEAM system has to include the ability to control the fiber guide orientation relative to the deposition velocity vector. Thus, the X-Y motion stages that execute the intra-layer trajectories are mounted on top of a rotary stage, coaxial with the nozzle. This is a significant addition when compared to the hardware and software components of a standard FFF printer. This configuration guarantees that the guided fiber enters the extrudate of the nozzle center is coaxial with the rotary stage axis (see Fig. 1.2).

To make robotic and electromechanical components, copper wire was selected as the fiber in the FEAM process. Figure 1.3 shows a SolidWorks (Dassault Systèmes, Waltham, MA) model of an idealized result of an individual FEAM trace with an electrically-conducting single copper fiber encapsulated in a clear thermoplastic extrudate. A rounded edge rectangular profile is typical of material extrusion type
additive manufacturing processes. The material of the extrudate is selected for the application at hand. In the case of soft robots Thermoplastic Elastomers (TPEs) are chosen and extruded in a custom extruder designed for the TPEs in Thermoplastic Elastomer Additive Manufacturing (TEAM) [72]. The combination of FEAM and TEAM processes allow for the rapid design, prototyping, and production of soft robots.

Figure 1.3. SolidWorks CAD model of an idealized FEAM output: a copper wire encapsulated in a clear thermoplastic.

Current FEAM technology consists of entirely open-loop control of the motion of the positioning axes, with the exception of the rotary axis which is on a PID controller. The fiber feeding and guide positioning relies entirely on good alignment of the stages, nozzle, and fiber guide. There is no feedback information during the process of how well-centered the fiber is within the extrudate, or even if it remained in the extrudate. The fiber feeding mechanism is placed on an independently controlled
3-axis stepper motion system. In contrast to an abrupt right angle, when printing a
continuous fiber trace along a curve it is readily observed that the fiber deviates from
the center of the extrude. At small radii the deviation effect of the fiber may result
in the exit of the wire from the extrudate and a build failure.

To avoid such failures compensation strategies that adjust the fiber positioning
during printing are investigated. The first proposed strategy is to create an angular
velocity ceiling. This ceiling will permit straight segments to be printed at maximum
speed, but when a curved path is encountered the tangential velocity is reduced if the
resulting angular velocity would have been greater than the predefined ceiling. This
strategy is possible because additive manufacturing lends itself to trajectory planning
offline from printing. In addition to an angular velocity ceiling, an independent motion
axis is added to the FEAM system to influence the position of the fiber as another
compensation strategy. Because the FEAM system requires a rotary motion system
the rotary system is also investigated for its capability to influence the final location
of the fiber during encapsulation. Each of the investigated strategies are different
variations on an open loop strategy due to the difficulty of closing the control loop.
Problems with using a closed loop control in this system include space near the fiber
guide and nozzle is severely limited, as well as the availability of sensors to detect the
fiber position. None of the investigated strategies are subject to these difficulties.

However, if these difficulties are overcome, closed-loop control strategies could
further improve the performance of the FEAM process as well as permit even more
potential geometries to be printed. This would require the use of a sensor to measure
the position of the fiber in situ. An optical sensor such as a camera could be utilized
with the matrix material is transparent, however the stacked layers of extrudate
produced by the 3-D printing process results in a very noisy background that needs
to be differentiated from the foreground. Using macro lenses to focus the image on
the just-deposited extrudate could help, however the severe space limitation near the nozzle makes this difficult to accomplish. An alternative sensor may be an electric field antenna, or magnetic field sensor depending on the material chosen for the fiber. However, problems with these types of sensor could result from encapsulated fibers on adjacent traces or nearby layers, as well as the length of the current segment. A Proportional-Integral-Derivative (PID) controller may work well for controlling the Y’ position of the guide.
Chapter 2
FEAM SYSTEM DESIGN

The Fiber Encapsulation Additive Manufacturing system consists of four main motion axes seen in Fig. 1.2. Figure 2.1 places these axes in the context of the other motion axes. On top of three $\theta$-X-Y stages is the build surface. The first stage is the $\theta$ stage mounted on top of a base plate. This stage rotates about a fixed axes. On top of the $\theta$ stage are the two linear X and Y stages with planar motions that define the actual desired workpart trajectory. Because the rotary motion axis is fixed, the extrudate nozzle can be mounted coaxial to this axis. This alignment simplifies programming and synchronization among axes significantly where the $\theta$ stage simply has to be pointed in the direction tangent to the path of the planar X-Y motion. Mounted separately is a more robust linear stage making up the vertical Z motion. Any extruder such as a commercial off-the-shelf filament extruder, or the custom miniature screw extruder [72] used with TEAM, can be mounted to the Z motion stage (see Fig. 2.1). Additionally, mounted to the Z stage is another 3-axis stepper-driven linear motion system on which the cutter feeder and fiber unspooling system is mounted. The second 3-axis stepper motor system provides fine adjustments to position the fiber guide directly under the nozzle, and can retract the guide tube when not in use.

When all the stages are synchronized, a fiber is encapsulated in an arbitrarily planar or 3-D shape, such as a helical coil. In total there are X, Y, Z, X’, Y’, Z’, Feeder, and two extruder axes (E1 and E2) connected to stepper motors. The $\theta$ rotary motion is connected to a quadrature encoded brushless servo. A solenoid actuates
the cutter. The cutter is a double-edge razor blade that cuts the fiber at a 0.127 mm (0.005 in) gap in the fiber guide. The blade is retraced by spring steel. Resuming feed on the fiber will push sequential fiber segments through the guide. Although FEAM can function well with passive fiber feeding, guaranteeing positioning with powered feeding is desirable for reliability. Calibrated power feeding eliminates tensioning in the encapsulated fiber that results in residual strain.
2.1. Design of the FEAM Machine

The experiments are performed on a custom-designed Fiber Encapsulation Additive Manufacturing printer. The main functional components of this equipment is shown in Fig. 2.1. These components are mounted on a frame on top of an aluminum base. The aluminum base has overall dimensions of 76.2 x 76.2 x 2.54 cm (30x30x1.0 in), and is made out of 6061-T6 aluminum. Threaded holes (1/4-20 UNC) are positioned in the base for mounting the $\theta - X - Y$ stage, along with the 80/20 (80/20 Inc., Columbia City, IN) frame members. The frame made of the inch-sized T-slot extrusion series made by 80/20 Inc. The larger portions of the frame are the 2-inch extrusions (80/20 parts 8020-2020) as well as 45.72 cm (18 in) 45° 1-inch (2.54x2.54 cm) cross members (80/20 parts 8020-2567/8) for bracing the sides of the frame together. The larger sections include all vertical and horizontal members. Insider corners of the frame are reinforced by triangular gussets (80/20 parts 8020-4136/8). The extrudate filament spool holder, Z-stage, and everything attached to the Z motion axis is attached to horizontal members at heights of 57.15 cm (22.5 in) and 67.31 cm (26.5 in) above the base.

With this base and frame setup, the machine is designed to have more capability and versatility than might otherwise be required for this implementation of the FEAM process. In order to maximize the FEAM capability the rotational axis was chosen to be underneath the X-Y axes so that any size or variety of extruder and cutter-feeder hardware could be tested without having to redesign a rotational motion for each type of device attached. The rotational $\theta$ axis is model RA-5D-4-SR by Newmark Systems (Rancho Santa Margarita, CA). It is driven by a brushless servo that has a quadrature encoder attached to it. All other motor axes are driven by stepper motors. A multi-channel slip ring for transmitting power and signal with no limit on the number of consecutive turns possible. On top of the $\theta$ axis is the X-Y axes
both comprising of NLS4-8-25 (Newmark Systems) motion stages mounted 90° to each other. On top of the final carriage is a 6061-T6 aluminum mounting plate that has been custom designed to support a variety of build platforms and includes three 120 thread-per-inch fine-adjustments and three press fit dowel rods for repeatable alignment and leveling.

The build platforms used here are also custom made out of 6061-T6 aluminum. They have a circular 24V 8-inch 350 W heating pad from Quintessential Universal Building Devices (Little Rock, AR) mounted with silicone adhesive to the underside and a RTD (PR-20-2-100-1/4-2-E-T) from Omega Engineering, Inc. (Norwalk, CT) is in internal contact with the aluminum. On top of the build platform is carefully layered polyimide tape. Polyimide film tape is used to contain ceramic fiber insulation between the build platform and mounting plate. A schematic of these main functional components can be seen in Fig. 2.1.

The vertical motion axis is also a Newmark Systems NLS8-200-101 linear motion stage. This axis can support up to 41 kg and provides support for a wide range of extruder and cutter-feeder hardware. As seen in Fig. 2.2. The first plate is mounted directly to this axes and attached to it are the smaller combined X'-Y'-Z' motion axes. The X' and Z' axes are MSL-25-11 stages, and the Y' axes is MSL-100-11 both also from Newmark Systems. Attached to these axes is a fiber spool holder which is simply a bearing on a steel rod and 3-D printed attachments depending on the spool the fiber comes on. Attached further to the Y' stage is the cutter-feeder mechanism which un-spools the fiber, feeds it via knurled rollers under the solenoid actuated double-edge razor blade cutter and finally out of the guide tube at the end.

The cutter-feeder mechanism is shown in Fig. 2.2 with a detail in Fig. 2.3. The guide tube is built using 304 stainless steel hypodermic tubing with ID of 0.2032 mm (0.008 ± 0.0005 in) and wall thickness of 0.1016 mm (0.004 in) manufactured by Vita
Needle (Needham, MA). Three segments of hypodermic tubing guide the fiber to the feed rollers, then the cutter, and finally underneath the extruder nozzle.

The selected fiber for testing is 0.127 mm (36AWG, 0.005 in) tin-coated copper wire. Copper is selected for its high electrical conductivity, availability, and cost ($8 USD per 975 m of wire). The feeding mechanism is driven by a dowel rod that has been knurled and coupled to a NEMA 17 stepper motor SM-42BYG011-25 (Mercury Motor, Shenzhen, China). Underneath, the cutter-feeder has polyimide tape heaters and thermocouple to pre-heat the fiber inside the tubes, set at 85 °C. Coiled about the final stage hypotube is a single exposed nichrome wire attached to a variable DC power supply E3610A (Agilent Technologies, Santa Clara, CA) and heated to 260 °C. A preload spring is attached to the plate on the Z motion axes to prevent backlash in the X', Y' and Z' axes from affecting the position of the hypotube.
Attached to the first Z axes plate is another plate with fine adjust screws, to which extruders or other devices can be attached. The fine adjustments allow for precision alignment of the extruder nozzle with the fixed rotational axis of the $\theta$ stage.

Attached to the frame is a DinoLite AD7013MTL(R4) video microscope (AnMo Electronics Corporation, Hsinchu 300, Taiwan). The extrudate filament spool holder consist of a bearing and steel plate with 3-D printed attachments depending on the type of spool. The hot ends used are from Printrbot extruders, now available as Ubis 13 hot ends. An array of CN145 temperature controllers from Omega Engineering is used to control a variety of heating devices with a large number of different types of temperature sensors including RTDs, thermistors, and thermocouples.

A NI USB 6008 (National Instruments, Austin TX) is used for digital output to control the cutter-feeder solenoid used to cut the fiber. The cutter-feeder solenoid is a Ledex 123423-030 push or pull continuous solenoid (Johnson Electric, Shatin, NT,
Hong Kong), which drives a rod which engages the cutter.

Motion on both stepper and servo motors is controlled by a GalilMC (Rocklin, CA) DMC 4183 which has 8 axes for synchronous motion required for synchronization of the X, Y, Z, \( \theta \), two extruder axes (E1 and E2), and fiber feeding axis. This controller has internal stepper drivers SDM-44140 and SDM-44040 from GalilMC. The servo motor driver is a Copley Controls (Canton, MA) 503 DC Brushless Servo Amplifier and is used with the \( \theta \) axes. The X’, Y’, and Z’ axes are controlled by a DMC-2143 that has three C8051F123 (Silicon Labs, San Jose, CA) based stepper motor drivers. Using the DMC-2143, the motion on the X’, Y’, and Z’ stages can be synchronized to the DMC-4183 controller.

### 2.2. Motion of the FEAM Machine

The build platform mounted to the X and Y stages can be seen in Fig. 1.2. If the nozzle is centered over the area labeled Nozzle Point in the figure which is coincident with the Z axis as well as the rotational axes of the \( \theta \) stage, then the only condition required to be maintained for fiber encapsulation is that the orientation of the \( \theta \) stage is aligned to the X-Y velocity direction. Since the X, Y, Z, \( \theta \), two extruder axes, and fiber feeding axis are all on one controller, this motion can be synchronized.

The strategy for information management and process flow is shown in Fig. 2.4. The process block diagram shows the experimental setup with all use-cases active. In many portions of the print some but not all use cases will be active. The first use case is when there is no fiber, and motion does not include the X’, Y’ or Z’ axes. In this case a model is made using SolidWorks. This model geometry is exported as a stereolithography file (.stl) and a slicing tool such as KISSlicer (www.kisslicer.com) is used to convert the geometry into trajectory segments for a traditional FFF printer. To convert this G-Code, which is commonly used by open-source 3-D printers as well
as commercial 3-D printers, to a form that is readable by the controller, a custom
script was written. The output is in Galil code format (.dmc). A custom National
Instruments LabVIEW program sends it to the DMC-4183 controller over Ethernet.
The program sends a buffer of motion segments to the controller. As the buffer
empties the LabVIEW program will refill it until there are no more segments available.

![Figure 2.4](image-url)

Figure 2.4. Block diagram showing the information, programming, and control flow
of the FEAM printer.

When FEAM-specific code (highlighted in green in Fig. 2.4) is used these code
segments are hand-programmed using G-Code which are then converted into the Galil
code using the script. This G-Code is then added to the KISSlicer generated G-Code
or run independently of it. Additionally new commands were created to control the
solenoid cutter. These digital and analog signals are sent from LabVIEW to the NI
USB 6008 to control their respective hardware.
In cases where the secondary axes are used, such as after segment motion and during the Y’ compensation strategy tests, the DMC-4183 must communicate with the DMC-2142. The DMC-4183 communicates over its own Ethernet session with the DMC-2142. It sends configuration information that was embedded in the converted G-Code and starts asynchronous motion on the X’, Y’, and Z’ axes. When synchronization is needed, a digital input and output on both controllers is used to provide nanosecond-scale interrupts to begin execution simultaneously. This two-way communication is used to synchronize the motion in the Y’ compensation strategy tests.
2.3. Prototype Components & Devices

Using the hardware and software of the Fiber Encapsulation Additive Manufacturing test bed, a variety of active components and devices have been produced. These devices combine both actuators and sensing devices. Many of the following devices are designed as proof-of-concept devices. Some, such as the capacitive pressure sensor were analyzed for their performance properties [61].

Figure 2.5. Helical coils produced using the FEAM technology.

After prototyping the FEAM printer with a 1-D system to demonstrate the various capability a fully 3-D FEAM environment might have, the first FEAM components
that were produced were various helical coils. The reasons that these components were produced first is that it is a 3-D shape that does not require interlayer junctions, the shape is relatively easy to program, and there is a wide assortment of electronic devices that depend on coiled wire. They are easy to program because a planar motion of a circle on the X-Y stage is needed as well as a constant $\theta$ axis rotation and a constant vertical Z motion. Shown in Fig. 2.5 are various helical coils, starting with the smallest that has a diameter of 6.35 mm (0.25 in). Coils smaller than this diameter were difficult to print even with the planar velocity reduced significantly. These problems depended significantly on the radius of curvature of the helix, the tangential velocity of the X-Y circular motion, as well as the printing temperature. One difficulty encountered with this programming setup is that the program assumed that all layers are helical coils, including the first. Often in material extrusion based 3-D printing, the first layer is the most difficult. In these manually programmed tests, it was found that starting the part by producing an extrudate-only section on the first few layers prevented interactions of the fiber with the build platform. Wire was subsequently introduced by manually indexing Y’ axis. The motion pushed the fiber guide into the extrudate. Additionally it was possible to anchor the wire into these helical coils without active feeding while utilizing slow X-Y planar velocities. However, in each case manually adjusting the Y’ position and iteratively converging on a desired location for a particular configuration was required. This resulted in many failed attempts for each configuration and was a significant detriment to the functionality of the FEAM process.

A 3D-printed speaker was prototyped using FEAM to demonstrate some of the possible functionality of a single helical coil of copper wire. This design consists of an extrudate-only cone printed up-side-down, and a helical coil printed directly on top of the cone (see Fig. 2.6). The coil is encased inside a permanent magnet. The
length of the coil was designed to have approximately 8Ω of DC resistance and was subsequently connected to an 8Ω impedance stereo amplifier. Once attached to a source of music, relatively clear music was produced for a proof-of-concept speaker.

Another prototype based on helical coils is a Linear Variable Differential Trans- former (LVDT) transducer. This prototype device consists of the same helical coil stacked on top of itself three times. When the coil needed to be terminated and a second coil started, the Y’ axis was used to bias the hypotube outside of the extrudate flow without interrupting wire feeding. This resulted in extrudate only sections with excess wire available as terminals for each coil. When the next coil started the Y’ was moved back to the pre-configured location and the extrudate recaptured the fiber upon freezing. The resulting three coils were connected to an LVDT test circuit and the prototype was capable of transforming the input signal as a magnetically soft
material was passed coaxially through the sensor (Fig. 2.7.)

In order to build complex electro-magnetic devices it is necessary to create electrical junctions \textit{in situ}. These junctions provide the capability for branching electrical traces as intralayer junctions, as well as cross-layer conductivity through interlayer junctions. To create these junctions various formulations of Electrically Conductive Polymer Composite were created and then deposited as part of the FEAM process. Strategies tested for extrusion include filament feed as in classic FFF printing, a miniaturized screw extruder, as well as developing methods for extrusion using compressed air driven heated syringe extruders. Prototype junctions can be seen in Fig. 2.8. This is still an area of active research [73].
In addition to being able to produce components, it is important to be able to integrate components into a FEAM printed device, and other electrically active 3-D printed components [79]. A strategy for incorporating Surface Mount Devices (SMD) into a FEAM part was tested with the production of a flashlight. In this instance FEAM and TEAM [11, 72] technologies were combined. Figure 2.9 shows the corresponding schematic of the approach. FEAM fiber segments were laid out in

Figure 2.9. SMD devices are added to a combined FEAM and TEAM printed prototype. Schematic shown on the left, and prototype on the right.
a planar pattern in a single layer. Utilizing the compliance of the soft thermoplastic elastomers, a hole roughly the size of the SMD component was built into the 3-D printing process. The fiber trace pattern is laid out in the desired circuit. The fiber is designed in this situation to overhang the hole at precisely the location of the contact pad on the underside of the SMD component. Subsequently extrudate is used to cover the fiber. In this fashion an SMD component can be placed vertically within the 3-D printed volume and electrical connections met by location and held together by friction and compression of the thermoplastic elastomer. A prototype flashlight demonstrating this technique is shown in Fig. 2.9. A resistor, LED, and battery are added to the FEAM and TEAM printed device, and connectivity is made by compression from the elastomer. Since a switch is not included, two bare leads in the circuit are manually touched together to complete the circuit.

FEAM permits simple designs for electronic components. As an example, a single pushbutton is produced by placing the FEAM fiber traces normal to each other on subsequent layers. It is possible to feed the fiber without extrudate. If a fiber such as bare copper wire is chosen then the gaps between fibers on subsequent layers can be used to create a pushbutton effect. Printed on top of the extrudate-less fiber is more extrudate positioned to allow an end-user to press on the region where the wires overlap. A connection is made when the elastic plastic extrudate is deformed such that the regions of exposed wire are touching. A prototype design for this type of device is shown in Fig. 2.10. In addition to detecting manual input, this device could be designed into 3-D printed devices. Examples could include pressure vessels which could detect when the inside pressure hit a critical threshold resulting in a usable digital signal.

The capability to 3-D print force sensors using various techniques is of research interest [51, 56, 64, 65, 66, 67, 69]. Combining FEAM with TEAM allows for the de-
sign and 3-D printing of sensors that respond to applied force. A capacitive pressure sensor prototype was designed for this purpose and consisted of several layered regions. A hard bulk layer, made of the ABS-based thermoplastic Bendlay (Kai Parthy, Germany), was the base for a square spiral wire coil that approximates a conductive plate. A bulk layer of a thermoplastic elastomer, MD6942 (Kraton, Houston, TX), was used as the deforming middle region. A second square spiral wire coil and finally another harder bulk layer of Bendlay completed the sensor. The sensor is shown in Fig. 2.11(a). The square coil shown in Fig. 2.11(b) creates the conductive plates of
Figure 2.11. A capacitive force sensor composed of 3 bulk extrudate layers with the inner layer being more compliant. Conductive plates are approximated with square wire spirals.

The capacitive pressure sensor. Since the bulk elastomer layer deforms more readily than the hard polymer layers embedding the coils, a relative displacement of the capacitor plates occurs under applied load. The resulting capacitance change can be measured [61]. Figures 2.11(e-e) show the schematic for the sensor. The resulting capacitive force sensor can be printed independently or embedded in the volume of a larger design. Capacitive sensors are of interest due to the wide variety of design geometries possible for specific applications [84] and the customization available from additive manufacturing.

It is possible to build complete systems as illustrated by a solenoid fabricated entirely within one print as shown in Fig. 2.12. The moving core of the solenoid consisted of a cup supported by 3-D printed extrudate-only flexures protruding from the
Figure 2.12. Monolithically printed solenoid with FEAM spiral coils, interlayer junctions, soft magnetic core, and PVA sacrificial material.

solenoid frame. The cup was filled with Soft Magnetic Composite (SMC) deposited in a flexure-suspended Bendlay-printed cup to create the core of the solenoid. The stacked spiral coil has interlayer junctions to carry current from the lower terminal to the upper terminal. Polyvinyl alcohol (PVA) was used as a sacrificial support material to be able to build the curved flexures seen at the top of the part, as well as guarantee the clearance between moving parts. The monolithically produced solenoid took about 20 hours to produce as the process was not run at full speed.

The monolithically built solenoid is a considerable modification to the complexity and design of the FEAM process. A heated stepper-driven syringe extruder was added to deposit the molten SMC into the cup to create the core. A solenoid-operated
compressed-air driven syringe extruder was used to deposit solder paste in the cavities containing bare FEAM fibers at electrical junctions between encapsulated FEAM spirals. A 6 W 1064 nm laser with a fiber optic cable, collimator, and focusing lens was used to flow the solder paste after deposition. These items are in addition to the secondary filament extruder used to deposit the sacrificial PVA.

As demonstrated by the fabrication of the prototype solenoid and capacitive sensor, Fiber Encapsulation Additive Manufacturing lends itself to the ability to directly 3-D print an active device designed on a computer.
Chapter 3

THE FEAM FIBER CENTERING PROBLEM

The introduction of a solid fiber into the extrudate flow creates disturbances in the flow resulting in a displacement of the coaxial fiber and extrudate composite from the programmed trajectory. Slowing the in-plane speed can reduce these manufacturing errors. In additive manufacturing, the total process time can be very long, and many additive manufacturing techniques suffer from lengthy build times [49]. Slowing the FEAM process further is not an attractive mitigation strategy. Even with the build platform feed speeds reduced to very small velocities, some geometries are not possible with FEAM due to the shear induced by the fiber on the liquid extrudate. The thermal conduction from the nozzle to the extrudate keeps the extrudate liquid while printing at very slow small velocities. The lateral forces between the fiber and extrudate will still displace the fiber and extrudate from centerline. To make more geometries possible and to avoid reducing speed, compensation strategies to improve the performance of the FEAM system are proposed, experimentally tested, and measured.

3.1. The Output of Fiber Encapsulation Additive Manufacturing

The output of the FEAM process is a composite consisting of matrix material similar to the ones used by traditional FFF techniques, and an encapsulated fiber of a different material. In addition to defects introduced by the fiber, the resulting composite is still subject to problems arising in the class of material extrusion printing, such as voids [54]. The fiber material has to be selected such that the fiber integrity is
preserved during the entire process. The fiber can enhance the structural properties (anisotropy, strength, stiffness, etc.), or/and the electrical and magnetic functionality.

Figure 3.1 is a view normal to the plane of the exit of the fiber guide, aligned with the tangential velocity of the current extrudate trace as the trace forms a curve. The blue oval represents an idealized version of the extents of the extrudate in this plane. The green profile indicates one type of observed extrudate flow regime where the extrudate flow around the fiber but does not reknit on the underside of the fiber. The material flowing underneath the fiber does not completely fuse with the previous layer, resulting in reduced strength.

Since the fiber is a continuous strand, having fibers in unknown locations can result in fibers torn out when the nozzle passes during printing. If the fiber is being used for structural reinforcement and if it is not in its intended location or torn from its encapsulating extrudate, then the built part will not function with the original design intent. Additionally if the fiber is intended for carrying electrical current, maintaining centeredness of the fiber in the extrudate is important to prevent shorts,
and ensure the safety of the device and the user. Extrudate flow asymmetric about the fiber can push the fiber in either direction, compounding the negative effects.

The main hardware limitation with the current design is the rotational velocity of the $\theta$ stage with the mass of two other leadscrew driven linear stages, mounting plate, and hardware attached to it. Better understanding the limitations of the process itself and the physical hardware of the printer is a secondary goal from increasing the design space is to improve performance of the hardware. For example it may be possible to operate the system at close to the hardware limits thereby significantly decreasing build time.

3.2. The Effect of Printing Parameters

While running FEAM experiments to encapsulate copper wire in straight lines with extrudates such as Bendlay and Kraton D1161, it is readily observed that the centering of the wire within the extrudate depends on multiple parameters during the build process. Ultimately FEAM depends on being able to reliably position the fiber inside the extrudate. This capability is important to ensure the stability of the process, ensure reliability of parts produced by FEAM, and allow for a greater design space.

For example, at a large given tangential velocity and small radius of curvature, the fiber will not remain encapsulated resulting in a failed build. This concept is shown in Fig. 3.2. The figure consists of a top view of the FEAM process with the extrudate exiting the nozzle and turning at a angle angle in the X-Y plane. The FEAM composite trails behind the nozzle. The extents of the extrudate are indicated by the red lines, the fiber location is indicated by the green line, and the center of the extrudate is indicated by the blue line. The desired fiber trajectory is the target location of the FEAM process. A tight radius of curvature illustrates just
one parameter which can displace the fiber from the extrudate.

During the FEAM and FFF fabrication techniques the melted extrudate freezes along a complex 3-D surface that trails behind the nozzle. This is typically not a problem for FFF processes since inside the extrudate there is very little internal shear stress, but it can result in stringers during a jump behind parts. Some FFF printers utilize techniques such as brushes to clean the nozzle and eliminate stringers during the process [75]. Since the freezing front is a complex surface, and the extrudate materials typically melt to various degrees over ranges instead of single defined melting temperatures. This property of both processes is difficult to measure and model. The figures in the following sections reproduce this schematic but highlight the effects of different FEAM print properties and parameters.
Ultimately the goal is to position the frozen fiber location, indicated by the green line, coincident with the center of the extrudate, indicated by the blue line. This can be achieved by a combination of remaining within certain design parameters and controlling how the fiber is encapsulated by the wire.

Based on experimental observations the following properties and parameters appear to have a significant effect on where the fiber freezes in place:

1. Tangential Print Velocity
2. Path Radius of Curvature
3. Freezing Front Location
4. Fiber Material Properties
5. Liquid Extrudate Properties
6. Relative Fiber-Guide and Nozzle Position

From observations, the tangential print velocity has an effect on the final resting location of the fiber within the extrudate. When producing a workpart with FEAM a single continuous helical coil the Y position of the end of the hypotube has to be adjusted for a given tangential velocity. Increasing the tangential speed of the FEAM process during the production of a single continuous helical coil requires adjustment of the Y' position of the hypotube in order to re-stabilize the FEAM process.

Using microscope imagery it is observed that the radius of curvature of the coaxial fiber in assorted samples has an impact on the ultimate location of the fiber. Adding compressed air cooling downstream of the extrudate nozzle will move the freezing font closer to the nozzle reducing the trailing distance and the space available for the fiber to travel in unfrozen extrudate. Changing fiber and matrix material also results in different corrections needing to be applied to re-center the fiber within the extrudate.
Table 3.1 shows a summary of these properties, methods available for their control and their implementation difficulty. Hardware permitting, planar velocity, \( v_t \), and angular velocity \( \omega \) are fully programmable and will be design parameters investigated for determining a compensation strategy. Unfortunately the radius of curvature is dependent on the design of the work part to be produced, and is therefore assumed unmodified in terms of the design of the part. However since radius of curvature in a particular path does effect the location of the fiber, it is a significant property of interest. The freezing front location is difficult to both sense and determine its location because of it’s complex shape and material dependency. The fiber material properties for some builds can be chosen for their specific properties, however in many case it is not possible to modify, and with the current hardware and software it is not possible to modify in the printing process without pausing and starting an entirely new fiber segment. The temperature of the hot end block, as well as the end of the hypotube and hypotube pre-heat locations is readily obtainable, however because the time constant of these materials is too high the temperature cannot be quickly modified on a per-segment basis. Likewise the strongly non-Newtonian nature of the extrudate fluid cannot be readily modified on a per-segment basis reducing it’s usefulness for managing the fiber location.
Table 3.1. Summary of In-Process Build Parameters and Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Sensing Difficulty</th>
<th>Control Difficulty</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity ((v_t, \omega))</td>
<td>Fully Programmable</td>
<td>Fully Programmable</td>
<td>Syncronized</td>
</tr>
<tr>
<td>Radius of Curvature ((\rho))</td>
<td>Programmable</td>
<td>Geometry Dependent</td>
<td>3-D part design limits possibilities</td>
</tr>
<tr>
<td>Freezing Front</td>
<td>Difficult</td>
<td>Difficult</td>
<td>Complex 3-D shape w/ no defined edge</td>
</tr>
<tr>
<td>Fiber Material Properties ((E, I, G,\ldots))</td>
<td>Single Choice of Fiber</td>
<td>Cannot Modify</td>
<td>Design Dependent (current, strength, etc)</td>
</tr>
<tr>
<td>Temperature ((T))</td>
<td>Easy</td>
<td>Small Range</td>
<td>Time constant too large</td>
</tr>
<tr>
<td>Viscosity ((\nu))</td>
<td>Difficult</td>
<td>(\nu(T))</td>
<td>Strongly non-Newtonian</td>
</tr>
</tbody>
</table>
Chapter 4

EXPERIMENTAL SETUP

Characterization of the output of the Fiber Encapsulation Additive Manufacturing (FEAM) system is conducted in order to specify parameters for various control strategies to overcome the FEAM process deficiencies. The goal of these experiments is to characterize the types of printing parameters that cause deviation from the centerline and failure of the fiber to remain inside the extrudate. Subsequently, this data will be used to develop strategies that will allow for greater design freedom by expanding the FEAM design space. Measurements are taken on samples produced in a repeatable and semi-automated way with the goal of quantitatively determining what happens to the fiber and extrudate composite under various printing conditions. These printing conditions are designed to yield useful information about the FEAM process such that fiber printing deficiencies can be used to generate mitigation strategies.

4.1. Turn Radius

From observed output of the FEAM process the turn radius has a strong impact on final wire position. At small radii geometries such as 3.125 mm (0.125 in) radius helical coils, the FEAM process breaks down. These small helical coils are very difficult to impossible to produce without compensation. With experimentation it is readily found that smaller turns can be made with re-positioning of the hypotube, reducing the tangential velocity, and applying air cooling to the extrudate. Discovering where the turn radius failure occurs and how to account for it is important to be able to
reliably print arbitrary trajectories. When failure occurs due to too small of a radius, applying one of the tested compensation strategies to the process programming can help produce these geometries. While these geometries are possible to fabricate by slowing the entire process significantly the planar velocity becomes impractical such that small builds will take and exorbitantly long time if they have significant numbers of small FEAM features.

Figure 4.1. Schematic of the Horseshoe pattern showing a 180° turn with various constant radii of curvature. Additionally the test pattern shows the three before control traces and the three after control traces. All of the channels have the same dimensions. Units are millimeters. Dimensions are to the centerline of the traces. Turnaround traces are supported by the pattern that extends outside the rectangular region.

Since the radius of curvature has a strong impact on FEAM failure, a standard test specimen consisting of a series of concentric 180° arcs printed on top of a square base made of the extrudate material was designed (see Fig. 4.1). The concentric arcs
are of various radii in increments of 3.175 mm, the smallest of which has a radius of 3.175 mm.

The goal of the set of experiments is to learn when failure occurs, and what changes to the FEAM process parameters and trajectory planning are required to achieve centering of the fiber inside the extrudate.

Figure 4.2. Top-view schematic showing effect of turn radius shown in (a) a moderate turn radius, and (b) a small turn radius with failure.

4.2. Tangential Velocity

Tangential velocity of the fiber and extrudate composite as it is printed is important for the quality of the print. From parameter testing, it is clear that slow velocities permit smaller radii turns as well as right-angle turns. This is true when the fiber is copper wire and the extrudate is either Bendlay or Kraton D1161. Additionally many radii are not possible at higher tangential velocities due to the relative bending force required to keep the fiber in the extrudate and the relative position
of the freezing front. Thus, it is desirable to include the tangential velocity of the process as a parameter of interest. Optimizing for tangential velocity has the potential to significantly increase the throughput. From parameter testing it is clear that the tangential print velocity has an effect on the final resting location of the fiber within the extrudate. When producing with FEAM a single continuous helical coil the Y direction position of the end of the hypotube has to be adjusted. Increasing the tangential speed of the FEAM process during the production of a single continuous helical coil requires further adjustment of the Y’ position of the hypotube in order to re-stabilize the FEAM process.

Figure 3.2 shows the idealized centerline of the fiber (blue line) and the actual location the fiber (green line.) The deviation between the two lines will increase as tangential velocity, \( v_t \), increases.

4.3. Tangential Velocity

Velocity is one of the most readily controlled parameters of the entire print process since the design of the control program has the tangential velocity stored as a variable for each upcoming segment. Additionally, the tangential velocity indirectly affects other properties of the system such as angular velocity, extrudate flow velocity, required hot end block internal temperature, freezing front location, material extrusion fusion to the previous layer, and adherence to the build platform.

4.3.1. Extrudate Heating

The material selected for FEAM testing as the extrudate is Bendlay. For proper material adhesion the extrudate must be heated to above the melting temperature and extruded through the hot end block and nozzle onto the 3D printed work part. In addition to being non-Newtonian, the extrudate fluid properties such as viscosity
have a strong dependence on temperature. Since changing the temperature of the relevant components takes a significant amount of time, a constant setpoint on the hot end block/nozzle assembly was used throughout all of the tests.

4.3.2. Fiber Heating

The extrudate is required to be in the liquid state as it exits the nozzle. There is a heat flux from the hotter extrudate to the cooler fiber. This heat flux effects the final position of the fiber within the extrudate and the wetting and co-adherence of the extrudate material to the fiber. Additionally it has been experimentally observed that by heating the fiber, thereby reducing the heat flux from the extrudate (and potentially prematurely freezing the extrudate) the final vertical position of the fiber can be influenced. Fundamentally this is a conduction problem between the hot extrudate and the circular fiber coupled with fluid flow as the extrudate forms around the fiber and fuses to the surrounding extrudate from previous trace trajectories. A single setpoint temperature was observed to be sufficient to achieve vertical centering and co-adherence. The minimum required fiber temperature should be used since higher temperature fibers will allow the fibers to more easily exit the extrudate under bending stress.

4.3.3. Active Extrudate Cooling

During the printing process as the extrudate and fiber leave the active site of the process, the extrudate is still molten. The freezing front lags behind the nozzle finalizing the fiber encapsulation. The region between the freezing front and the nozzle remains liquid and it is possible for the fiber to exit the extrudate due to further bending stresses. This effect was observed prominently for smaller radii curves. Adding active extrudate cooling has been observed to reduce the exiting of the fiber from the extrudate by causing, the outer surface of the extrudate to freeze more
quickly, pushing the freezing front closer to the nozzle.

Using a nozzle with compressed air for extrudate cooling has proven successful. However it is desirable to find the temperature of the compressed air nozzle that improves the freezing front significantly without detracting from the melting and extrusion properties of the nozzle and hot end block.

![Diagram showing the freezing front and fiber paths](image)

**Figure 4.3.** Top-view schematic showing location of the freezing font a distance $l$ from the nozzle.
Chapter 5

EXPERIMENTAL PROCEDURE

Each experiment consists of printing one rectangular test plate base that is two layers thick with solid infill. Subsequently the FEAM fiber-extrudate composite layer is deposited in the pattern shown in Fig. 5.1. The test specimen contains two rectangular control traces without fiber encapsulation that serve to check the alignment of the printing nozzle with the rotary table axis. The subsequent trace includes the fiber and contains three regions. Two linear regions, one at the beginning and the other at the end, are used as control to verify the fiber insertion in the simplest configuration. The central region contains concentric horseshoe traces with decreasing turning radius.

5.1. Measurement Technique

The digital microscope camera was used to take images of assorted portions of the test plate. The calibration is done by aligning on-screen calibration marks to a workshop grade (+0.25−0.15 µm) gauge block placed 45° with respect to the image base. This is the worst case because it include maximal possible optical aberrations and is maximally misaligned with the image pixel orientation. Subsequently the calibration was verified with another workshop grade gauge block of different size to confirm on-screen measurements. This calibration allows for the single-pixel size to be accurately determined and provides a metric between images and workspace dimensions.
Figure 5.1. Schematic showing the location of the centers of the microscope images as red dots.
Figure 5.2. Schematic describing the location of each of the microscope images.

The microscope images were taken at selected locations on the test specimen as indicated as red dots in in Fig. 5.1 and labeled as “EXTRUDATE CONTROL” in Fig. 5.2. These images with no encapsulated fiber were taken from the rectangular traces printed before and after the fiber region was printed. These experimental controls are used to quantify the effect of drift in the nozzle alignment on extrudate during the printing phase, and to account for misalignments. Eight microscope images corresponding each to one of the sides of the squares are recorded. Three experimental control images with fiber, labeled “CONTROL 1-3,” were taken along the horizontal traces demonstrating the stability of the fiber encapsulation process at print time. Subsequently for each horseshoe pattern an image was taken at the lead-in, 0°, 45°, 90°, 135°, 180°, and lead-out locations. Another three images, “CONTROL 4-6,” were taken in horizontal sections printed after the horseshoes.
The path taken during FEAM fiber deposition is shown in Fig. 5.3 with the start and end location for the fiber segment indicated. Afterwards the inner fiberless calibration rectangle is produced. Data is sampled at the same red-dot locations for all specimens. From this figure it becomes apparent that all samples are processed by producing horseshoes in a clockwise motion. Further research could compare the opposite direction, however, there are no obvious physical properties of the system that would result in chirality in the process, with the exception of any misalignment and manufacturing imperfections. Manufacturing imperfections could include an out-of-round nozzle exit, non-parallel orientation of the plane where the nozzle terminates relative to the printing plane, and hysteresis effects of the motion stages. For this work, the backlash in the XY axes was measured and subtracted off for all data.

Figure 5.3. Schematic showing the print orientation of the continuous fiber within a single specimen. The fiber starts at the segment at the bottom right. The squares center-left do not contain fiber, and are used for calibration of the extrudate position.
Figure 5.4. Composite of cropped microscope images showing the extrudate controls (left), wire controls (top and bottom horizontals) and the largest 0.75in radius horseshoe for the corresponding test specimen.

A composite of the cropped images showing the extrudate controls (left), the wire controls (top and bottom horizontal images), and the largest horseshoe for the 0.650 in/sec speed is shown in Fig. 5.4.

By convention the images are stored as bitmaps with a size of 1280 by 960 pixels. A custom script written in MATLAB (MathWorks, Inc., Natick, MA) was used for
extracting numerical data from these images. The images are pre-processed using Adobe Photoshop CC 2015 (Adobe Systems, San Jose, CA) batch process to reproducibly crop the images to 460 by 460 pixels. The cropping operation focused on the center of the image where the region of interest is and seen in Fig. 5.5.

The hardware on the FEAM system was aligned to software graticule drawn in the Dino Capture 2.0 (AnMo Electronics Corporation, Hsinchu, Taiwan) software. Misalignment measured from the non-fiber experimental control compared to the software graticule was subsequently subtracted off.

The center of the software graticule was determined to be at the (232, 231) pixel location on the image. This location is considered to be the theoretical desired center of the extrudate since the system is aligned to this location. All reference displacements are measured from this location after calibration.

After being cropped, the MATLAB script shows onscreen each image in succession. The user manually selects points to record the extents of the measured features in the images. For the experimental controls that do not include a fiber, these are the upper and lower extents of the extrudate. For images that do include wires, the points recorded are the extents of the extrudate and the extents of the wire. This process is illustrated in Fig. 5.6.
Figure 5.5. Microscope image showing the full image taken, and the cropped zone indicated by the white box. The area of interest in this image is entirely contained within the cropping box.
Figure 5.6. Selected measurement locations for both an extrudate without a fiber and an extrudate with a fiber. The locations are indicated by black dots.
5.2. Calculations

Data extracted from images is in the form of X-Y coordinates corresponding to pixel locations of manually selected boundaries as described in Fig. 5.6. Additionally for each point a corresponding $\theta$ angle is assigned based on the position on the specimen. The points extracted from the images are described in the schematic shown in Fig. 5.7.

![Schematic of the coordinate system used for data extraction.](image)

Figure 5.7. Schematic of the coordinate system used for data extraction.

5.2.1. Extrudate Calculation

The goal of these calculations is to determine the location of the extrudate relative to the planned trajectory. These calculations apply to the extrudate in both traces without the wire (controls) and with encapsulated fiber. The thickness of the
extrudate can be calculated as:

$$\Delta x_e = x_2 - x_1$$ \hspace{1cm} (5.1)$$

$$\Delta y_e = y_2 - y_1$$ \hspace{1cm} (5.2)$$

where $\Delta x_e$ and $\Delta y_e$ are the thickness of the extrudate in the corresponding X and Y directions, $(x_1, y_1)$ is the point defining the lower edge, and $(x_2, y_2)$ is the point defining the upper edge of the extrudate. The actual thickness $\Delta s$ of the extrudate is calculated as:

$$\Delta s_e = \Delta x_e \sin(\theta) + \Delta y_e \cos(\theta)$$ \hspace{1cm} (5.3)$$

The displacement from the planned trajectory centerline can be obtained as:

$$\tilde{x}_e = \frac{1}{2}(x_1 + x_2) - x_c$$ \hspace{1cm} (5.4)$$

$$\tilde{y}_e = \frac{1}{2}(y_1 + y_2) - y_c$$ \hspace{1cm} (5.5)$$

where $x_c$ and $y_c$ denote the centerline position in the image. This centerline is known because the system was previously calibrated to it using the software image graticule in the DinoCapture software. The total displacement from the programmed centerline at every location along the horseshoe traces is:

$$\tilde{s}_e = \tilde{x}_e \sin(\theta) + \tilde{y}_e \cos(\theta) - s_{drift}$$ \hspace{1cm} (5.6)$$

where $s_{drift}$ is accounting for the drift of the nozzle alignment during the fiber encapsulation traces. It is calculated from the data measured on the control rectangles printed right before and after the FEAM traces. The percent displacement is then calculated as,

$$\tilde{s}_e\% = \frac{\tilde{s}_e}{\Delta s_e} \times 100\% .$$ \hspace{1cm} (5.7)$$
5.2.2. Wire Calculation

The goal of the wire calculations is to determine the displacement location of the wire relative to the programmed location. Equations for determining the thickness and displacement from the trajectory planned centerline of the wire are nearly identical to that of the extrudate, since the data takes the same form as \((x_3, y_3)\) and \((x_4, y_4)\) and the calculation goal is the same:

\[
\Delta x_w = x_4 - x_3 \quad (5.8)
\]

\[
\Delta y_w = y_4 - y_3 \quad (5.9)
\]

\[
\Delta s_w = \Delta x_w \sin(\theta) + \Delta y_w \cos(\theta) . \quad (5.10)
\]

Then,

\[
\bar{x}_w = \frac{1}{2} (x_3 + x_4) - x_c \quad (5.11)
\]

\[
\bar{y}_w = \frac{1}{2} (y_3 + y_4) - y_c \quad (5.12)
\]

\[
\bar{s}_w = \bar{x}_w \sin(\theta) + \bar{y}_w \cos(\theta) - s_{drift} \quad (5.13)
\]

and

\[
\bar{s}_w\% = \frac{\bar{s}_w}{\Delta s_w} 100\% . \quad (5.14)
\]

The calculations for the extrudate and wire are combined and used to quantify the effect of embedding the wire on the position of the extrudate in the FEAM process. For each set of fabrication parameter values three specimens were produced and measured. An average and sample standard deviation were calculated to show variation within specimens using the same printing parameters.
Figure 5.8. Microscope camera alignment can result in errors in edge detection on extrudate and fiber extents.

5.3. Error Analysis

5.3.1. Systematic Errors

There are several sources of systematic error in the measurement technique that influence results from the microscope camera. First, rotational misalignment of the microscope camera frame relative to the X-Y plane: \( \lambda \) angle alignment error about the z-direction. The impact on the data results in a small angle error. The typical calculated value of \( \lambda \) was 0.16° measured using the DinoCapture software. This misalignment has a minimal impact on the thickness and displacement from centerline due to its small magnitude. Second, the misalignment of the microscope camera from the normal to the X-Y plane is quantified as angle \( \gamma \) shown in Fig. 5.8. This error is roughly canceled out because of the approximate circular cross-section of the extrudate and fiber. Third, there is a possible misalignment between the nozzle center axis and the position of the \( \theta \) axis as shown in Fig. 5.9. In order to minimize
Figure 5.9. Nozzle-θ axes misalignment can cause systematic measurement error, which is shown in this top view of the build platform.

this error, an alignment technique to identify and reduce it was developed. This technique is described in Appendix A.2. It is an iterative technique that results in a sinusoidal print if there is a non-zero nozzle-θ misalignment and a straight segment if the misalignment is zero. Based on the sinusoid amplitude the error can be estimated and corrections can be applied iteratively. Typically, after the alignment procedure the residual error was approximately 5µm on the X direction and 7µm on the Y direction.

The effect of these systematic errors translates into a bias from the programmed centerline. A partial compensation of these effects is performed using the $s_{drift}$ parameter obtained from the rectangular regions of extrudate-only traces.
5.3.2. Random Errors

A component of the random error is introduced by the user-based measurement process. The cross sectional shape of extrudate is pseudo-elliptical instead of rectangular. This difference in shape results in blurry edges in microscope photographs. When calibrating the microscope camera this systematic error is reduced by placing the focal plane of the microscope camera on the edges of the extrudate and not the top. However some blur persists resulting in a random error when the point on the edge of the extrudate is selected by the experimenter. In order to quantify the errors induced by the human operator, three sets of experiments were performed. The first human-induced random-error experiment is to quantify the immediate ability of the experimenter in choosing points repeatedly. This test was done by selecting

Table 5.1. Average and sample standard deviation as a function of location on the horseshoe pattern for 5 immediately subsequent data extractions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Avg. Extrudate Displacement $\bar{s}_e$ [µm]</th>
<th>Extrudate St.Dev. [µm]</th>
<th>Wire Average Displacement $\bar{s}_w$ [µm]</th>
<th>Wire St.Dev. [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead In</td>
<td>-23.4</td>
<td>1.7</td>
<td>6.2</td>
<td>2.4</td>
</tr>
<tr>
<td>0°</td>
<td>8.9</td>
<td>2.5</td>
<td>7.7</td>
<td>3.1</td>
</tr>
<tr>
<td>45°</td>
<td>28.1</td>
<td>2.9</td>
<td>32.7</td>
<td>2.5</td>
</tr>
<tr>
<td>90°</td>
<td>1.5</td>
<td>7.2</td>
<td>-3.1</td>
<td>6.1</td>
</tr>
<tr>
<td>135°</td>
<td>3.6</td>
<td>3.3</td>
<td>-16.2</td>
<td>4.0</td>
</tr>
<tr>
<td>180°</td>
<td>-43.7</td>
<td>3.5</td>
<td>-36.9</td>
<td>8.3</td>
</tr>
<tr>
<td>Lead Out</td>
<td>-16.6</td>
<td>2.3</td>
<td>3.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>
a set of seven images: the Lead In, 0°, 45°, 90°, 135°, 180°, and Lead Out. Each image from this subset was measured a total of five times. The calculations described in Section 5.2 were performed on the extracted numerical data points and then the average and sample standard deviation were calculated (see Table 5.1.) Overall the immediate repeatability was on the range of 2-8µm, with no significant differences between the measurements on the extrudate and the wire.

Table 5.2. Average and sample standard deviation as a function of location on the horseshoe pattern for five subsequent days.

<table>
<thead>
<tr>
<th>Location</th>
<th>Avg. Extrudate Displacement $\tilde{s}_e$ [µm]</th>
<th>Extrudate St.Dev. [µm]</th>
<th>Wire Average Displacement $\tilde{s}_w$ [µm]</th>
<th>Wire St.Dev. [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead In</td>
<td>-25.2</td>
<td>2.8</td>
<td>5.8</td>
<td>2.8</td>
</tr>
<tr>
<td>0°</td>
<td>9.8</td>
<td>3.2</td>
<td>9.8</td>
<td>0.8</td>
</tr>
<tr>
<td>45°</td>
<td>27.9</td>
<td>2.6</td>
<td>33.3</td>
<td>4.4</td>
</tr>
<tr>
<td>90°</td>
<td>4.6</td>
<td>3.4</td>
<td>0.3</td>
<td>7.2</td>
</tr>
<tr>
<td>135°</td>
<td>4.1</td>
<td>2.8</td>
<td>-13.7</td>
<td>5.9</td>
</tr>
<tr>
<td>180°</td>
<td>-43.4</td>
<td>4.8</td>
<td>-31.7</td>
<td>6.9</td>
</tr>
<tr>
<td>Lead Out</td>
<td>-14.5</td>
<td>0.8</td>
<td>8.0</td>
<td>4.9</td>
</tr>
</tbody>
</table>

The second human-induced error experiment was to quantify the ability of the experimenter to choose points consistently on different days. Each image from the set of was measured a total of five times across five distinct days. The average and standard deviation for this data is provided in Table 5.2.
A similar analysis including all measurement locations on the specimen is included in the Appendix A.1. This quantifies the experimenter-related errors relative to properties such as radius of curvature, $\theta$ location on horseshoe, specimen location, and rotary table angular velocity.
6.1. Uncompensated Results

To establish a baseline, specimens were produced using five different printing velocities, from 3.175 mm/s (0.125 in/sec) to 15.875 mm/s (0.625 in/sec). Six specimens, three with and three without encapsulated wire, were fabricated for each velocity. Each position on the specimen, with the exception of the calibration rectangles, was given a position number, as illustrated in Fig. 6.1. For each set of experiments the data is presented on a series of four plots. The first plot shows the displacement from centerline as a function of position number for each velocity. The second plot shows displacement vs. position on each horseshoe, and the third plot groups the data according to the radius of curvature. Each of these plots show curves for each fabrication velocity, averaged for the three identical specimens. The fourth shows the average effect of angular velocity at three locations on the curved part of the horseshoe traces. For all graphs the positive values represent displacement from centerline toward the inside of the curve, as seen from above.

Figure 6.2 shows the results for specimens printed without wire encapsulation. This indicates the overall accuracy of the modified printing process (with θ rotation.) The trajectory planning is exactly the same except no fiber is provided and the cutter-feeder is kept in the retracted position. This data uses the θ axes as if the fiber were being encapsulated in the process. This is implemented by setting the velocity of the fiber feed axes equal to zero while running an identical trajectory program.
In the first plot, Fig. 6.2(a), there is an obvious periodic behavior that correlates well with the $\theta$ position. Thus, it is clear that the geometry of the programmed trajectory influences the outcome. It is observed that separation between the extrudate and the previous layer occurs at a location on the trace with the smallest radius of curvature, and highest velocity. This corresponds with the highest $\theta$ angular velocity. The velocity effect can be inferred from the error vs angular velocity plot, Fig. 6.2(d). It is later shown that this separation is likely due to the lateral shear due to the inability of the $\theta$ axes to follow the planned trajectory. This demonstrates that the chosen parameters hit the limits of the design space for this hardware configuration.

From Fig. 6.2(c) it is observed that there is a displacement radially inward when

![Figure 6.1. Schematic of the numbering scheme for the Specimen Location numbers.](image)
Figure 6.2. Displacement of the extrudate from print centerline on the extrudate-only specimens.
there is a high angular velocity. Figure 6.2(d) also shows that for angular velocities \( \omega \leq 2 \text{ rad/sec} \), displacements from centerline are closely grouped at 5% or less.

The total error for all uncompensated specimens is calculated as the Root-Mean-Square Error (RMSE) value of the displacements from centerline, and was approximately 4.6% of the extrudate thickness. RMSE can be useful in measuring the net impact of error. Unlike standard deviation, which shows variation about the mean, RMS quantifies variation about zero. RMSE is calculated using the formula given for a set of errors, \( \{e_1, e_2, ..., e_n\} \) [80],

\[
RMSE = \left( \frac{1}{n-1} \sum_{i=1}^{n} |e_i| \right)^{1/2}.
\]

(6.1)

However outliers have a disproportionate impact on the RMS value [81]. Thus, measurements that include separation from prior layers were excluded from the calculation. The displacements shown in the subsequent Fig. 6.3 result from the introduction of copper wire as the coaxial fiber to the FEAM process. The corresponding RMSE nearly doubled to 9.1%. The variability among specimens of different planar velocities increases with the introduction of the fiber. Another observation is that the introduction of the fiber results in the flat or slightly reversed trend when looking at the relationship of displacement from centerline to radius of curvature in the horseshoe (Fig. 6.3(c).) Separation now results in extrudate and wire being pushed radially outward. This is consistent with the solid fiber resisting bending when compared to the liquid extrudate-only samples. Fig. 6.4 shows the impact on the displacement of the fiber which is similar to that of the extrudate, demonstrating that the extrudate moves with the wire. This change in trend can also be seen in the angular velocity data Figs. 6.3(d) and 6.4(d). Data points with higher angular velocities have successively more negative (more radially outward) motion. This deviation due to the addition of the fiber is undetectable in the data for lower planar and angular velocities.
Figure 6.3. Displacement of the extrudate from print centerline on the extrudate and wire specimens.
Figure 6.4. Displacement of the wire from print centerline on the extrudate and wire specimens
6.2. Error Compensation Strategies and Results

Based on the experience accumulated during system development, prototypes fabrication, and manufacturing of the uncompensated specimens the following error compensation strategies were identified:

- Limiting the angular velocity of the rotary table, $\omega_{max}$;
- Compensatory lateral displacement of the fiber guide, Y’ compensation;
- Over- and under-bending of the wire relative to the programmed path, $\theta_b$.

These strategies have been analyzed experimentally with identical specimen geometry, and the fabrication errors were compared with the uncompensated cases and among themselves.

6.2.1. Maximum Angular Velocity Strategy, $\omega_{max}$

The uncompensated specimens from the previous section demonstrated several trends that were consistent across the cohort. It was observed in the uncompensated data that increasing angular velocity above a threshold resulted in larger deviations from centerline of both the copper wire and the extrudate.

The $\theta$ axis is used to keep the nozzle direction tangent to the velocity of the planar motion as shown in Fig. 6.5. If the $\theta$ axis is unable to track the tangent trajectory, the out-of-tangent error can cause the fiber and extrudate to drift with respect to the ideal centerline.

Figure 6.6 shows the tracking error vs. reference $\theta$ angle for each uncompensated specimen configuration as reported by the GalilMC DMC 4183 controller. The color of the line indicates the planar tangential speed of the motion in the X-Y plane, and the symbol (diamond, square, triangle, etc...) indicates the radius of curvature for that location. Two sample configurations, shown in the colorized figure as green
and yellow were programmed to be $v_t = 12.700 \text{ mm/sec}$ and $6.350 \text{ mm/sec}$, with a radius of curvature of $r = 6.350 \text{ mm}$ and $3.175 \text{ mm}$ respectively. These parameters correspond to the same angular velocity $\omega = 2.0 \text{ rad/sec}$. It is observed that for all trace segments in which the angular velocity is $2.0 \text{ rad/sec}$ or less, the $\theta$ tracking error remains less than $\pm 1.1^\circ$. A tracking error of $\pm 1.1^\circ$ is smaller than the alignment of the hypotube with the X-axis performed using the microscope camera, thus it is not large enough to be discerned from the misalignment of the hypotube to the X-motion in the data.

For the curved segments, the compensation model is defined programmatically to satisfy the following equation: $\omega_{program} = \min\left(v_t/r, \omega_{max} = 2.0 \text{ rad/sec}\right)$. If necessary, the planar velocity is reduced to match the value corresponding to $\omega_{max}$. For the straight segments, $\omega = 0$, the velocity is maintained unchanged. This strategy is implementable without requiring the complication of adding more motion axes to the system. Thus, this strategy is simpler than some of the other strategies that require both supplemental hardware and additional software.
Figure 6.6. Tracking error vs. reference $\theta$ angle for each uncompensated specimen configuration. Angular velocity values are in rad/sec. Color shows $v_t$ and symbol shows radius.

Three specimens were produced for each of two overall print velocities, $v_t = 0.625$ in/sec (same as the largest uncompensated velocity), and $v_t = 2$ in/sec (which corresponds to the maximum velocity of the linear stages.) Looking closely at the results obtained from the specimens produced with this strategy (Figs. 6.7(a) and 6.8(a)), the periodicity along a specimen is maintained. However, the shape changes from roughly sinusoidal to linear beginning at $\theta = 0^\circ$. This change can be seen in Figs. 6.7(b) and 6.8(b). Throughout these results it becomes apparent that the extrudate and fiber move together. The rough linearity of the results implies that the process could further be tuned to make improvements based on both position along the horseshoe and radius of curvature, but would be difficult to implement in a more complex geometry.
Figure 6.7. Displacement of the extrudate from print centerline on the extrudate and wire specimens with $\omega_{max}$ compensation.
Figure 6.8. Displacement of the wire from print centerline on the extrudate and wire specimens with $\omega_{\text{max}}$ compensation.
For both the extrudate and the fiber, the results show a significant reduction in the variability for specimens produced with different velocities when compared to the uncompensated results. Nevertheless, no change to the overall RMS error was observed. An important improvement to this strategy compared to an uncompensated print is that no separation was observed even for significantly larger velocities used in the straight segments and large-radius arcs. This results in increased productivity with no loss in quality.

6.2.2. Compensatory Lateral Displacement, \( Y' \) Strategy

Another trend that was shown throughout the uncompensated specimens is that the deviation of the extrudate and fiber from the centerline was consistent at each position on horseshoe (same angle \( \theta \)) across all planar velocities. It was observed that the \( Y' \) alignment of the fiber guide to the nozzle had a significant effect on the final position of the fiber within the extrudate even in straight segments. These observations imply that it is possible to control the location of the fiber by moving the \( Y' \) stage on the curved segments to bias the position of the guide as shown in Fig. 6.9.

In effort to implement a strategy utilizing these observations, a compensating function of \( \theta \) is required. For example, the deviation from centerline as a function \( \theta \) can be approximated by a circular fit, as shown in Fig. 6.10. Since the motion is circular, and the fiber guide is tangent to the path, the algebraic compensation model is defined programmatically as: \( f(\theta) = a \sin \theta \). The amplitude \( a \) was chosen to be 70\( \mu \)m from the uncompensated data analysis. The \( Y' \) strategy is active for all arc segments.

In this implementation the DMC 4183 controls the major motion axes. As such the DMC 4183 is responsible for the straight segments, planar arc curves, rotational motion, extrusion, and fiber feeding. Based on the input planar velocities and a given
radius of curvature for each arc segment, the DMC 4183 calculates corresponding velocities on all axes. The configuration information for the current segment is sent over the Ethernet connection to the DMC 2143 controller. This calculates the corresponding velocity required to make the $Y'$ motion synchronize with $\theta$ as a function of time:

$$Y' = a \sin \theta$$  \hspace{1cm} (6.2)

Once the DMC 2143 calculates and reconfigures the motion for the specific segment, a digital input/output channel is changed to a $HIGH$ state in order to indicate to the DMC 4183 it is ready to begin motion. Once the DMC 4183 receives the $HIGH$ signal it sends a return signal on another DIO line to synchronize motions. This signaling implementation is chosen to overcome the latency of the Ethernet network which includes queuing the packets for sending, switching the packets between ports on the hardware switch, and reading the packets from the packet queue on the incoming
Ethernet side. This accumulation of lag, combined with the fact that Ethernet does not guarantee timeliness or order of received packets results in signals that can be delayed as much as 100 ms or greater. According to the manufacturer, the DIO interrupts can respond on the order of nanoseconds, resulting in a better synchronized process.

The results show that the linearity of the displacement from centerline vs the $\theta$ position of the horseshoe is very similar to that of the $\omega_{max}$ strategy. A reduced (or more negative) amount of displacement in both cases is found on the lead-in data point than at the $\theta = 0^\circ$ data point. In all samples at $\theta = 0^\circ, 90^\circ$ the extrusion process produced free flowing extrudate at the beginning and ending of each arc segment. This increases the difficulty of measuring the extrudate extents. Indicated in both Figs. 6.11 and 6.12 are points that experienced separation for the largest velocities. These are probably due to the tracking error on the rotary table, similar to the uncompensated case.
Figure 6.11. Displacement of the extrudate from print centerline on the extrudate and wire specimens with Y’ compensation.
Figure 6.12. Displacement of the wire from print centerline on the extrudate and wire specimens with Y’ compensation.
A reduction in the process variability among samples, resulting in tighter grouping of data was observed. The RMS error was reduced by 25% in both the extrudate and the fiber measurements.

One significant drawback of the Y’ strategy is that it requires a new motion, which increases the complexity and cost of the system.

6.2.3. Over- and Under-Bending, $\theta_b$ Strategy

The $\theta_b$ strategy for fiber centerline compensation uses an existing motion axis. The strategy consists of modifying the angle of the fiber guide with respect to the planar velocity:

$$\theta_{program} = \theta + \theta_b(\theta)$$

(6.3)

where an over-bending corresponds to $\theta_b > 0$ and under-bending to $\theta_b < 0$. The schematic showing the Over- and Under-Bending strategy is shown in Fig. 6.13.

![Figure 6.13. Over- and Under-Bending strategy biases the $\theta$ angle of the guide relative to the path.](image)

73
The test specimens consist entirely of arc segments immediately preceded and followed by straight segments. In order to achieve continuous motion on the $\theta$ axis, the arc segment boundary conditions of $\theta_{\text{begin}} = 0$ and $\theta_{\text{end}} = 0$ are imposed on the motion. This creates a restriction on the function we can choose for $\theta_b(\theta)$. Even with these ends conditions imposed on $\theta_b$, there is a discontinuity from infinity to a finite value in terms of radius of curvature in the trajectory planning of the controller. In order to accomplish this two separate sections of code are used and the controller will transition between the two segments. The velocity of motion on all stages momentarily vanishes during the code transition and motion resumes after the next code block begins. This will not effect the comparison between this strategy, previous strategies, and the uncompensated specimens since this happens on all cases.

![Graph](image_url)

Figure 6.14. Linear approximation for $\theta$ over/under bending used to approximate the error of the fiber position in the extrudate.
The over- or under-bending amount was chosen to be the piece-wise function:

\[
\theta_b(\theta) = \begin{cases} 
  a\theta & 0 \leq \theta \leq \frac{\pi}{2} \\
  -a(\theta - \pi) & \frac{\pi}{2} \leq \theta \leq \pi 
\end{cases} \tag{6.4}
\]

that linearly approximates the errors in the uncompensated specimens as shown in Fig. 6.14. The sign choice of the \( a \) parameter determines over or under bending. The test specimen series include choices \( a = -5, -1, 1, 5 \) with units of percent of \( \theta \).

The results from the \( \theta_b \) strategy with \( a = \pm 5\% \) have significant displacement for both the extrudate and wire, in excess of 150\% and 200\% respectively (Figs. 6.15(a) and 6.16(a).) These compensatory displacements are well beyond the useful limits. Since \( \theta_b \) alters only the programmed position of the wire, the high values of extrudate displacement demonstrate that the wire position has a significant effect on the final location of the extrudate. These results were not included in the final data analysis.

When looking exclusively at the \( \pm 1\% \) results the errors are similar with the uncompensated specimens for both the extrudate and the wire.
Figure 6.15. Displacement of the extrudate from print centerline on the extrudate and wire specimens with \( \theta_b \) compensation.
Figure 6.16. Displacement of the wire from print centerline on the extrudate and wire specimens with $\theta_b$ compensation.
6.2.4. Pre-Bending, $\theta_b$ Strategy

The $\theta_b$ Pre-Bending Strategy attempts to better control the frozen location of the fiber within the extrudate by utilizing information obtained from the $\theta_b$ Strategy (Section 6.2.3) and integrating it with the fact that there is a discontinuity in path curvature before and after the arc segments. Pre-bending strategy potentially orients the fiber more favorably for the subsequent arc segment. The implemented $\theta_b$ for the arc segments on the specimens was:

$$\theta_b(\theta) = \begin{cases} 
    b(\theta - \frac{\pi}{2}) & 0 \leq \theta \leq \frac{\pi}{2} \\
    -b(\theta - \frac{\pi}{2}) & \frac{\pi}{2} \leq \theta \leq \pi 
\end{cases}$$  \hspace{1cm} (6.5)

The resulting profile for $\theta_b$ is shown in Fig. 6.17. Choices of $b$ were $-5^\circ$ and $-10^\circ$. The absolute displacement was chosen to bias the fiber enough that it would result in the fiber freezing near the centerline without pushing the fiber out the sides of the

![Figure 6.17. Pre-bending implementation (red) compared to the over- and under-bending (pink and cyan.)](image)
extrudate. Additionally, the negative direction choice was informed by the results of the Over-Under-bending strategy. Test specimens were fabricated with a transition delay of 1000 ms introduced to determine if there are any flow and freezing effects during the transitional period between the straight and arc segments. At the end of the arc, the θ stage will index back to zero while the planar motion, extrudate, and fiber feeds wait for this to complete.

The results presented in Figs. 6.18(a) and 6.19(a) show that this strategy does remove a significant portion of the periodicity along the specimen. Nevertheless, the amplitude of the errors are similar to the uncompensated case. Adding delay at the beginning of the arc segment did not improve the results. At the points corresponding to the highest angular velocity and smallest radius of curvature, separation was seen more often than in specimens fabricated using the other strategies.

By far, the θb Pre-Bending strategy resulted in the largest removal of periodicity when compared to the other strategies. However, this removal of periodicity also comes with larger RMS error.
Figure 6.18. Displacement of the extrudate from print centerline with $\theta_b$ Pre-Bending compensation.
Figure 6.19. Displacement of the wire from print centerline with $\theta_b$ Pre-Bending compensation.
The novel Fiber Encapsulation Additive Manufacturing process is an extension of the Fused Filament Fabrication technique. It provides new possibilities for additive manufactured composite materials, including fiber reinforced and electrically conductive composites. It enables monolithic fabrication of active and smart devices and structures with embedded sensors, actuators, and power circuitry.

The capability of correctly encapsulating the coaxial fiber within a single extrudate trace is required to reliably produce FEAM printed parts. Creating compensation strategies capable of mitigating the anticipated errors in the FEAM process is essential for fulfilling the full potential of the technology. These compensation strategies are realizable due to the predictive nature of 3-D printing: a trajectory is programmed ahead of time by 3-D modeling and slicing software, and adjustments can be calculated \textit{a priori}.

The experiments conducted for FEAM process analysis consisted of fabricating 59 specimens with different manufacturing parameters and error compensation strategies. A total of 3,304 locations were measured and quantified. Table 7.1 summarizes these fabrication configurations and the number of specimens analyzed.

Figure 7.1 shows that the uncompensated extrudate only specimens (UC-EO-E) produced an RMS error of approximately 4.6% of the extrudate width from the programmed centerline location. The error bars indicate the average range of the error across different fabrication parameters. Introducing the wire to the uncompensated specimens (UC-EW-E) resulted in nearly doubling both the RMS error of the
Table 7.1. Manufacturing configurations and specimens grouped by compensation strategy.

<table>
<thead>
<tr>
<th>Description</th>
<th>Specimens per Configuration</th>
<th>Configurations</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability Test</td>
<td>5</td>
<td>1</td>
<td>Higher number of specimens for better error management.</td>
</tr>
<tr>
<td>Uncompensated No-Wire</td>
<td>3</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Uncompensated With Wire</td>
<td>3</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>$\omega_{\text{max}}$ Strategy</td>
<td>5</td>
<td>2</td>
<td>Fewer configurations necessary by design of strategy.</td>
</tr>
<tr>
<td>Y’ Strategy</td>
<td>3</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$\theta_b$ Strategy</td>
<td>1</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

extrudate and the average range of errors across the specimens. This shows that the addition of the fiber to the process significantly influences the position of the extrudate. The following notations were made to label the bars corresponding to the different compensation strategies: $\omega_{\text{max}}$ strategy is shown as C-WM-*, the Y’ strategy is shown as C-YP-*, Over/Under-bending strategy is shown as C-OB-*, the Pre-Bending is shown as C-PB-*, and the Pre-Bending with Delay is shown as C-
Table 7.2. Summary of specimen sets.

<table>
<thead>
<tr>
<th>Expression</th>
<th>Description</th>
<th>Extrude</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC-EO-*</td>
<td>Uncompensated Extrudate-Only</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>UC-EW-*</td>
<td>Uncompensated Extrudate w/ Wire</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-WM-*</td>
<td>$\omega_{\text{max}}$ Strategy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-YP-*</td>
<td>$Y'$ Strategy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-OB-*</td>
<td>Over-/Under-Bend Strategy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-OB-*-1</td>
<td>Over-/Under-Bend Strategy 1% Only</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-PB-*</td>
<td>Pre-Bend Over-/Under-Bend Strategy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>C-PBD-*</td>
<td>Pre-Bend Over-/Under-Bend &amp; Delay Strategy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

PBD*. The “*” denotes either “E” for extrudate or “W” for wire. The naming scheme is summarized in Table 7.2.

Comparing Figs. 7.1 and 7.2 shows that the wire and extrudate generally move together with approximately the same RMS error and cross variability within the broad specimen category. The cross variability, $CV$ is calculated by,

$$CV = n^{-1} \sum_{j=1}^{n} (\max(\tilde{s}_j) - \min(\tilde{s}_j)),$$

(7.1)

where $j = \{1, 2, ..., 48\}$ is the specimen location and $\tilde{s}_j$ set of displacement errors at location $j$ for a given class of data. The result is smaller cross variability results in more closely agreeing displacement across tested parameters with that strategy or set given as an absolute magnitude. The $\omega_{\text{max}}$ strategy improves the positioning of the wire slightly more than the extrudate, in terms of RMS error. However, the variability among specimens was reduced approximately in half when compared to
the uncompensated with-fiber specimens. Most importantly the $\omega_{\text{max}}$ compensation strategy was successful in preventing separation from the prior build layer for all configuration parameters.

Overall RMS error in specimens produced using the Y’ strategy was reduced by 26% with about the same cross variability as the $\omega_{\text{max}}$ strategy specimens. Unlike the $\omega_{\text{max}}$ strategy the Y’ strategy specimens have nearly identical improvement in the RMS error on both the extrudate and the wire positioning. The Over/Under-strategy at ±1% showed only slight RMS error changes with no apparent improvement in the variability across specimens. This can be seen in both Figs. 7.1 and 7.2. The $\theta_b$ Pre-Bending strategy improved the RMS error for the wire but not for the extrudate. Adding the delay at the beginning of the arc segments produced larger errors and cross variability.

Tables 7.3 and 7.4 show a color coded summary of the results. Each column represents compiled data from each selection of strategies. In purple are the values from the

![Figure 7.1. RMS error on extrudate vs. strategy applied. Error bars illustrate the range of variability within the specimen category.](image)
Figure 7.2. RMS error on wire vs. strategy applied. Error bars illustrate the range of variability within the specimen category.

uncompensated specimens without fiber, representing standard additive manufacturing. Once fiber is introduced the experimental control (UC w/ Wire) is the reference to which the rest of the data is compared. Each subsequent column shows data from each compensation strategy. The average percent displacement from centerline for all data in each category and the corresponding sample standard deviation are shown as “Average Error” and “StDev”, respectively [24]. The RMS error quantifies the displacement from the ideal centerline while the Range is the absolute difference between the most positive and most negative displacements from centerlines. The “Cross Variability” shows the average error range across all specimens produced with the respective strategy. Each row with a formula $R(E : x)$ shows the Pearson Correlation Coefficient, $R$, [58] for the error, E, compared to the corresponding properties: tangential velocity ($v_t$), radius of curvature ($r$), and angle on the horseshoe ($\theta$). Colorization of green, gray, and red have been chosen to highlight obvious improvement, no discernible change, and worse results in terms of the value analyzed compared to
Table 7.3. Summary of Results by Compensation Strategy on Extrudate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UC w/o Wire</th>
<th>UC w/ Wire</th>
<th>$\omega_{\text{max}}$</th>
<th>$Y'$</th>
<th>$\theta_b$ 1%</th>
<th>$\theta_b$ PB</th>
<th>$\theta_b$ PB D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Error (%)</td>
<td>-1.5</td>
<td>-3.2</td>
<td>-3.6</td>
<td>-1.9</td>
<td>-3.1</td>
<td>-2.5</td>
<td>-5.4</td>
</tr>
<tr>
<td>StDev (%)</td>
<td>4.4</td>
<td>8.5</td>
<td>8.4</td>
<td>6.5</td>
<td>8.2</td>
<td>9.2</td>
<td>11</td>
</tr>
<tr>
<td>RMS Error (%)</td>
<td>4.6</td>
<td>9.1</td>
<td>9.1</td>
<td>6.7</td>
<td>8.7</td>
<td>9.4</td>
<td>12</td>
</tr>
<tr>
<td>Cross Variability (%)</td>
<td>3.8</td>
<td>11</td>
<td>4.6</td>
<td>4.8</td>
<td>6.6</td>
<td>N/A</td>
<td>14</td>
</tr>
<tr>
<td>Range (%)</td>
<td>32</td>
<td>38</td>
<td>35</td>
<td>36</td>
<td>37</td>
<td>46</td>
<td>60</td>
</tr>
<tr>
<td>R(E:$v_t$)</td>
<td>-0.04</td>
<td>0.15</td>
<td>0.21</td>
<td>0.06</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>R(E:$r$)</td>
<td>0.46</td>
<td>0.47</td>
<td>0.14</td>
<td>0.09</td>
<td>0.40</td>
<td>0.34</td>
<td>-0.01</td>
</tr>
<tr>
<td>R(E:$\theta$)</td>
<td>0.54</td>
<td>-0.30</td>
<td>-0.11</td>
<td>0.06</td>
<td>-0.53</td>
<td>0.24</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

Color Legend
- Standard
- Reference
- Improvement
- No Change
- Worse

the reference respectively. This analysis was done for both the Extrudate, seen in Table 7.3, and the wire in Table 7.4. The tables have N/A entries where specimens were not produced with variable tangential velocities.

Overall, all strategies improved the correlation coefficient of the wire with respect to radius of curvature. This is expected in cases of the $\omega_{\text{max}}$, $Y'$, and $\theta_b$1\% strategies where improvement is noticeable or marginal. However the improvement is also seen in the $\theta_b$ PB strategy where much of the periodicity with respect to angular position is removed resulting in a much improved correlation coefficient with respect to angular position.

In terms of extrudate displacement the $\omega_{\text{max}}$ and $Y'$ strategies have better performance. However in terms of positioning the wire inside the extrudate the $\theta_b$ Pre-
Table 7.4. Summary of Results by Compensation Strategy on Copper Wire

<table>
<thead>
<tr>
<th>Parameter</th>
<th>UC w/o Wire</th>
<th>UC w/ ( \omega_{max} ) Wire</th>
<th>Y'</th>
<th>( \theta_b ) 1%</th>
<th>( \theta_b ) PB</th>
<th>( \theta_b ) PB D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Error (%)</td>
<td>-</td>
<td>-1.8</td>
<td>-4.0</td>
<td>-1.8</td>
<td>-1.9</td>
<td>-2.0</td>
</tr>
<tr>
<td>StDev (%)</td>
<td>-</td>
<td>8.9</td>
<td>7.4</td>
<td>6.7</td>
<td>9.0</td>
<td>5.9</td>
</tr>
<tr>
<td>RMS Error (%)</td>
<td>-</td>
<td>9.1</td>
<td>8.4</td>
<td>6.8</td>
<td>9.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Cross Variability (%)</td>
<td>-</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>N/A</td>
</tr>
<tr>
<td>Range (%)</td>
<td>-</td>
<td>40</td>
<td>35</td>
<td>48</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>R(E:v_t)</td>
<td>-</td>
<td>0.25</td>
<td>0.41</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>R(E:r)</td>
<td>-</td>
<td>0.62</td>
<td>0.16</td>
<td>0.16</td>
<td>0.20</td>
<td>0.14</td>
</tr>
<tr>
<td>R(E:θ)</td>
<td>-</td>
<td>0.03</td>
<td>0.21</td>
<td>-0.11</td>
<td>-0.52</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Color Legend

- Standard
- Reference
- Improvement
- No Change
- Worse

Bending strategy also exhibits improved performance in reducing overall error and correlation coefficients.

In the Y' strategy had a greater overall impact on the performance improvement of the FEAM process. However, it requires an extra motion stage that increases the complexity and the cost of the system. The \( \omega_{max} \) strategy does not require additional motion axes to work, allows all linear segments to be run at full planar speed, and to slow down only on the arc segments in which the angular velocity would rise above the \( \omega_{max} \) ceiling. Thus, this strategy results in a higher performance for a large percentage of fiber segments in a given design. Additionally this compensation strategy does not require hardware above and beyond that required for the FEAM process itself, and only requires a slightly modified set of software programs.
The $\omega_{\text{max}}$ and $Y'$ compensation strategies could be combined to operate simultaneously since the input axes and motion control are independent of each other. The synergistic effect has the potential to both increase productivity and reduce manufacturing errors and process variability.

Currently all path segments that include fiber require manual programming. Integration of the fiber encapsulation programming with the computer-aided-design modeling and slicing software is an important step in the future development of FEAM. Moreover, the ability to do real-time fiber position sensing and developing closed-loop control strategies has the potential to further increase the productivity and manufacturing accuracy.
A.1. Semi-Automated Repeatability Results

To characterize the impact of the experimenter on the repeatability of the semi-automated measurement technique an experiment was performed. The experiment is to repeatedly measure the same specimen five times on all locations of interest on the specimen. This contrasts with the subset of the specimen points measured repeatedly in the experiments described in Sec. 5.3.2 by measuring all data points from the same specimen. The same vertically mounted microscope camera technique was used to extract data as described in Sec. 5.1. The resulting data set was in the same format as the uncompensated and compensated data and thus can be directly compared. The specimen was measured in each location five times. Then the standard deviation was calculated for these locations.

Figure A.1 shows the result of the experiment for the extrudate extents. Standard deviation peaked above 4% in location 30, and was near 4% at location 35. However most of the errors were below 2% of the extrudate.

Shown in Fig. A.2, the 90° location has the highest repeatability difficulty. Despite this, the standard deviations fell below 5% of the extrudate thickness everywhere on the specimen. This plot shows the average standard deviation averaged across constant horseshoe locations. Compared to the magnitude of the displacement measurements these introduced random errors are small.

Figure A.3 shows that there is not a strong relationship between the introduction of random errors by the semi-automated technique and the radius of curvature, and
Fig. A.4 shows a weak relationship with the 90° location.

The shape varies when comparing the results from the extrudate to that of the wire. Figures A.5, A.6, A.7, and A.8 the same plots except the wire is used instead of the extrudate.
Figure A.3. Standard deviation of extrudate extents vs. radius of curvature.

Figure A.4. Standard deviation of extrudate extents vs. angular velocity.
Figure A.5 shows that with the exception of the $\theta = 0$ location on the first largest horseshoe, the standard deviation of error measurement of the wire extents remained at 3% or below, with the majority of standard deviations concentrated around the $1\% \pm 0.5\%$ region.

![Graph of standard deviation of wire extents vs. position number.](image)

Figure A.5. Standard deviation of wire extents vs. position number.
Figure A.6. Standard deviation of wire extents vs. horseshoe location.

Figure A.7. Standard deviation of wire extents vs. radius of curvature.
Figure A.8. Standard deviation of wire extents vs. angular velocity.
Figure A.6 shows that the standard deviation of the extents of the wire did not vary more than $1 \pm 0.5\%$ in terms of angular variation on position on the horseshoe. Figure A.7 shows the relationship between the radius of curvature and the measurement error of the wire extents. With the exception of the largest radius of curvature, the standard deviation stays below 1.5% while on the largest radius of curvature it is over 2%. Figure A.8 shows that in terms of angular velocity during printing, the measurement repeatability is not significantly impacted. Overall, the repeatability of the measurement technique is better than the amplitude of the measured errors on the specimens.

A.2. Nozzle-$\theta$ Stage Alignment

The nozzle center must be concentric with the $\theta$ stage axis. The first alignment uses a zig-zag program pattern. The zig-zag pattern can be reduced in amplitude by improving the alignment between the nozzle and $\theta$ axis.

The zig-zag program makes a high-amplitude high-frequency square-wave pattern, but at the same time rotates the $\theta$ stage at a constant rate during the long segments (see Fig. A.9.) First, allow the program to build the first trace. If the nozzle is aligned this trace will appear completely straight with only minor optical aberrations due to the texture of the underside of the nozzle. If the nozzle is out of alignment with the $\theta$ stage, the trace will build a sinusoidal pattern. If it is far out of alignment it will build a looping pattern. Alternate printing the zig-zag with the long edges along the X and Y directions. When a new long segment begins move either the X or Y direction mount plate fine adjusts a small amount and observe the effect on the amplitude of the sinusoidal pattern by allowing it to print out a trace. Move either adjustment in the direction that minimizes the small sinusoidal pattern. Do this repeatedly on alternating the X or the Y direction adjusts until the amplitude
stops decreasing and then repeat the process alternating between X and Y adjusts. Switch between X and Y printing directions and X and Y adjustments. Inspection of the traces after printing and adjusting should be performed by inspecting the traces under the microscope camera.

Figure A.9. Procedure showing the planar path taken by the X and Y stages while rotating $\theta$ at a constant rate.
Bibliography


105


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