3D Printing Continuous Fiber Reinforced Thermoset Using 5-Axis Robot Arm

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Introduction

Thermosets and continuous fiber printing are both active area of 3D printing research due to these prints' favorable mechanical properties. In this research a 5-axis robot arm is employed to print a carbon-fiber thermoset composite fabricated in-situ. The angle of the tool relative to the printing surface is of special interest. By modifying this angle, the matrix-fiber ratio of the resulting composite is altered, allowing for the in-situ modification of the printed material's mechanical properties. Additionally, the printable volume is studied.

Figure 1 - Graphic Representation of Elevation Angle

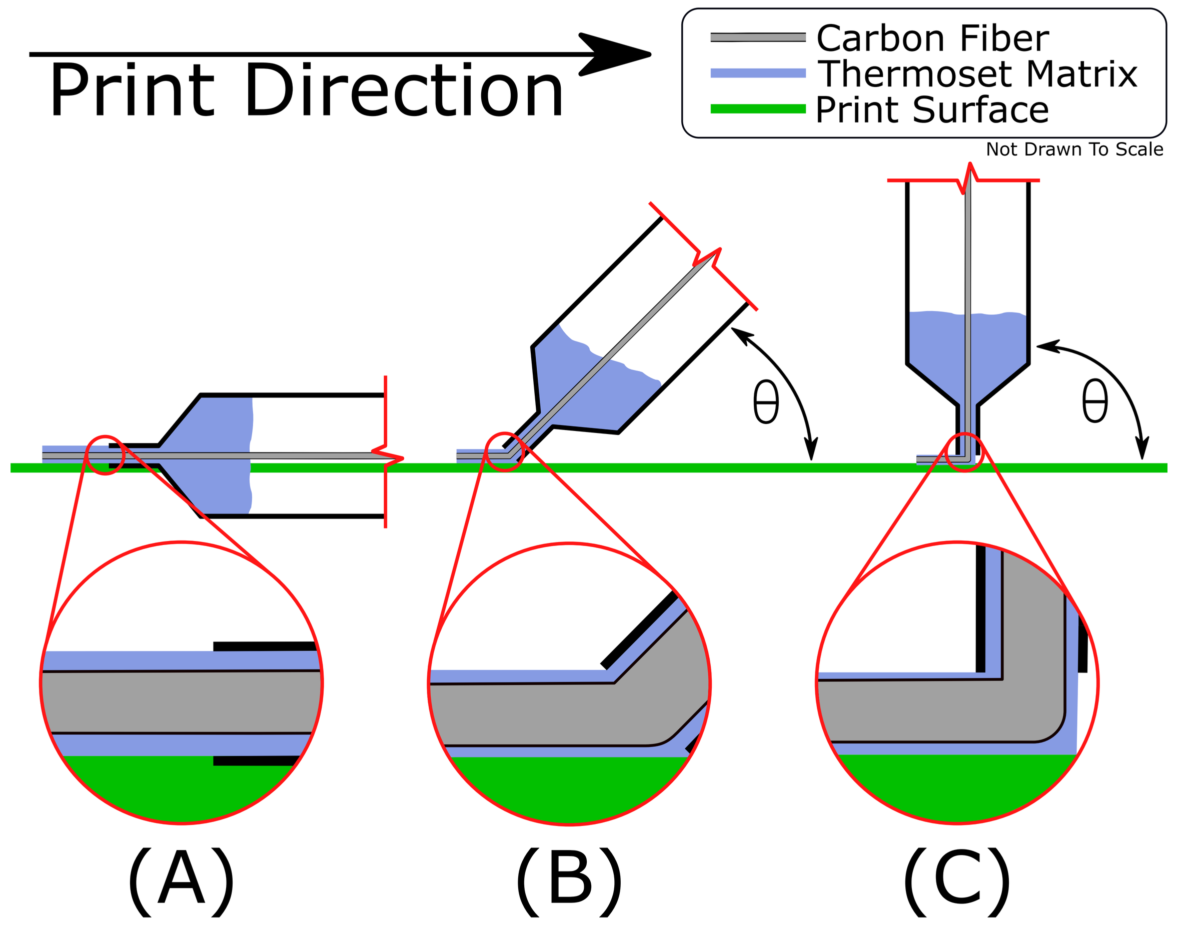
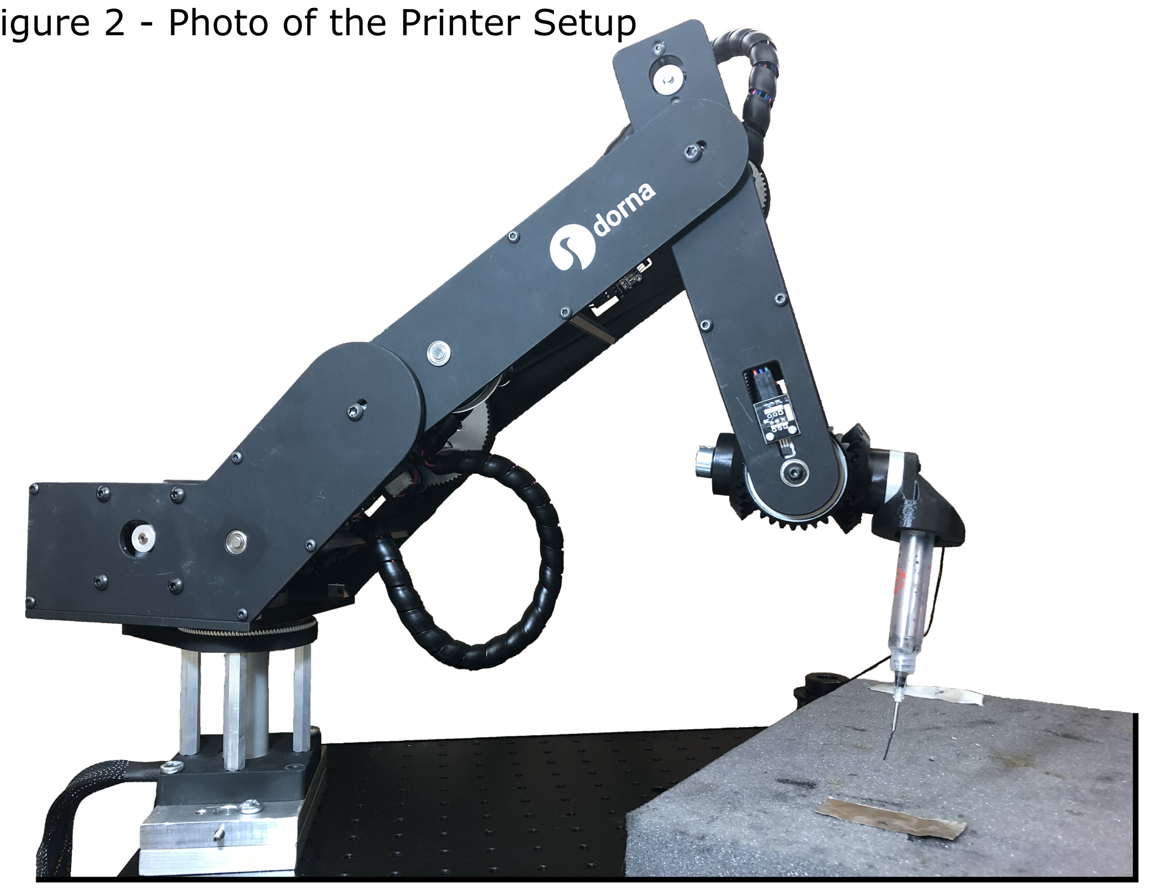


Figure 2 - Photo of the Printer Setup



Methodology

The printer was composed of a 5-axis robotic arm manufactured by Dorna robotics. A Temmco E1E03 syringe served as the end effector. The printing material is a two part composite. The matrix was formulated from a base of EPON828 Resin and placed in the syringe. IM10 carbon fiber was fed through the matrix to complete the composite. A custom software solution manages tool path generation and robotic arm control.

Elevation Angle

The elevation angle is the angle between the tool and print surface, denoted theta in Figure 1. This study explored how elevation angle alters the resulting composite. By holding the tool at specific angles, the ratio of matrix to fiber was be controlled. Samples prepared at specific elevation angles were employed to study the effects of elevation angle on linear density and tensile strength.

Software

To control the arm, commands are generated in python and sent to the robot arm. A custom script employed an inverse kinematics solution to convert path data from GCode files into commands executable by the robot. In order to transition between segments, commands were inserted to rotate the tool without moving the tip, which is necessary for the printing process.

Print Volume

Print volume constrains the geometry of a print that can be produced. In a 5-axis printer, the determination of volume is complex, however, by simulating a large representative sample of configurations, the volume can be determined.

Results

Mechanical Properties

Experimental data confirms that elevation angle influences the matrix-fiber ratio in the resulting print. Figure 3 shows the inverse correlation of linear density to elevation angle, while Figure 4 demonstrates the direct correlation of elevation angle to composite strength.

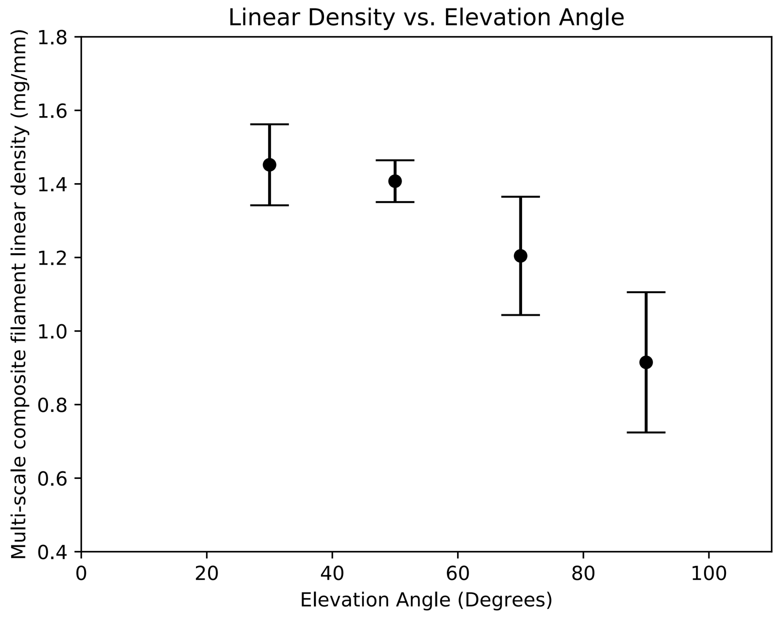


Figure 3 - A chart displaying the relationship between elevation angle and linear density in the resulting composite.

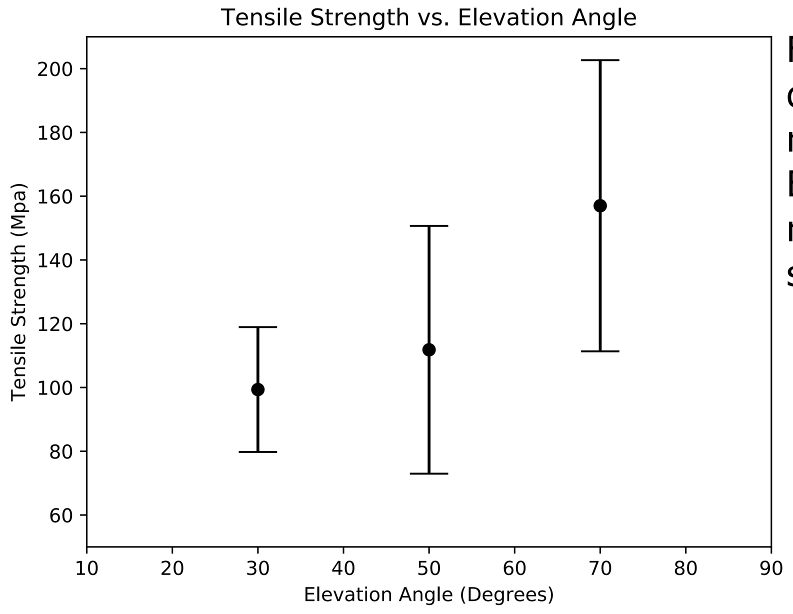


Figure 4 - A chart displaying the relationship between Elevation Angle and resulting composite strength.

Calculated Volume

Raw volume was determined to decrease with increasing Elevation Angle. However, volume weighted based on printability suggests that weighted volume ignores elevation angle. Printability is the measurement of how many configurations of the robot arm can reach the desired ending position. Some key volume related statistics are summarized in the table below.

Elevation Angle	Total Printable Area (sq. in)	Weighted Printable Area (sq. in)	Total Printable Volume (cu. in)	Total Weighted Volume (cu. in)	Total Printable Positions	Average Printability	Radial Printability	Average Radius
30	313.830	171.358	10.08E+6	4.99E+6	1.26E+05	0.546	7.94E+05	12.781
40	310.835	172.389	9.99E+6	5.04E+6	1.24E+05	0.555	8.02E+05	12.786
50	304.988	172.807	9.78E+6	5.06E+6	1.22E+05	0.567	8.05E+05	12.754
60	294.185	172.815	9.36E+6	5.06E+6	1.18E+05	0.587	8.06E+05	12.660
70	278.828	172.575	8.77E+6	5.06E+6	1.12E+05	0.619	8.05E+05	12.522
80	259.405	172.213	8.05E+6	5.05E+6	1.04E+05	0.664	8.04E+05	12.352
90	236.645	172.069	7.23E+6	5.05E+6	9.47E+04	0.727	8.04E+05	12.160

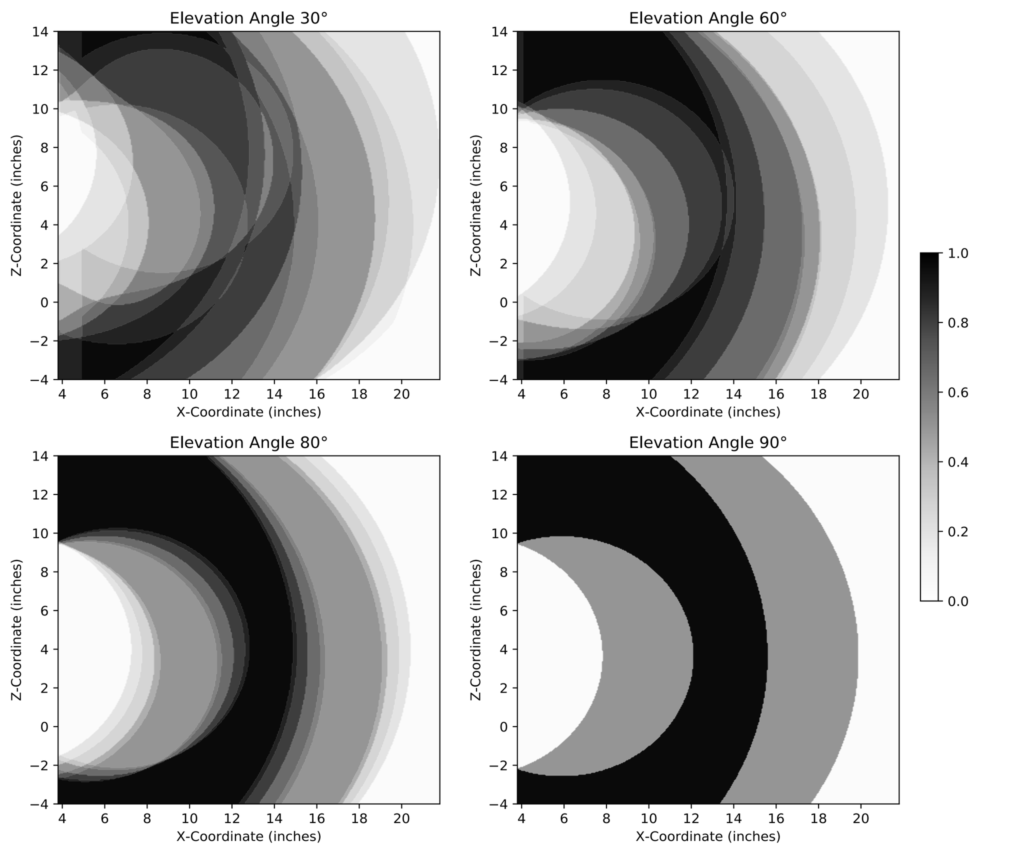


Figure 5 - Cross sections of the printable area for select Elevation Angles are shown. Darker regions indicate higher printability: more configurations of the arm can reach them. Regions with low printability are difficult to effectively operate in, making them less significant while printing.

Conclusion

In this research in-situ composite fabrication was studied. The parameter, elevation angle, was shown to influence the mechanical properties of the resulting composite. This allows for in-situ material modification, allowing for further customization in 3D printed parts. One such example would be designing a part with specific failure point without altering the exterior profile of the part. Finally, the study concluded with an exploration of the printing volume of the current 5-axis printer. One additional direction of study is introducing a secondary "rotational angle" parameter to better utilize the printable volume.

Acknowledgements

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